Lidar Turbulence Sensor Flight Results

Aviation Safety Program

Edward H. Teets Jr.,
NASA Dryden Flight Research Center

Weather Accident Prevention Annual Project Review
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ACLAIM Test Team

Aviation Safety Program

Edward H. Teets Jr.(PI), L. J. Ehernberger(Co-I), and Rodney K. Bogue(Co-I)
NASA Dryden Flight Research Center, Edwards, CA

Christopher E. Ashburn
AS&M, Edwards, CA

Philip Gatt(Co-I), Dale Bruns, John Herwig, Sara C. Tucker, Mark Vercauteren, and Scott Shald
Coherent Technologies, Inc., Lafayette, CO

Ivan O. Clark(Co-I) , Gary W. Grew, Philip Brockman, and Wayne Gerdes
NASA Langley Research Center, Hampton, VA

Carroll W. Rowland
Swales Aerospace, Hampton, VA

OUTLINE

- BACKGROUND
- OBJECTIVES
- PREVIOUS ACLAIM FLIGHT ACTIVITY
- FLIGHT CONFIGURATION
- FLIGHT CASE STUDIES
- SUMMARY
- FOLLOW-ON EFFORTS

Weather Accident Prevention (WxAP) Program

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- **Turbulence Prediction and Warning Systems (TPAWS):**
  Develop and augment knowledge of both the turbulence phenomena and the effects of turbulence on aircraft, and develop technologies to detect convection and *clear air turbulence* and mitigate the effects on aircraft passengers and crew.

- **Flight Demonstrate Conceptual Lidar-based Turbulence Sensor, WxAP Milestone #18**

- **Performance Assessment of Lidar-based Turbulence Systems, WxAP Milestone #25**

Turbulence Product Development Team Over-All Objective

- **Develop a robust detection capability that spans the full range of turbulence environments**
  - **Provide Timely Reliable Tactical Warning to:**
    - **Deviate,**
    - **Institute Cabin Safety Measures, and/or**
    - **Institute Mitigation Measures**
  - **Provide Real-Time Alerts to AWIN Network**

Complete Turbulence Detection Capability Provided through Dual RF and IR Wavelength Radar

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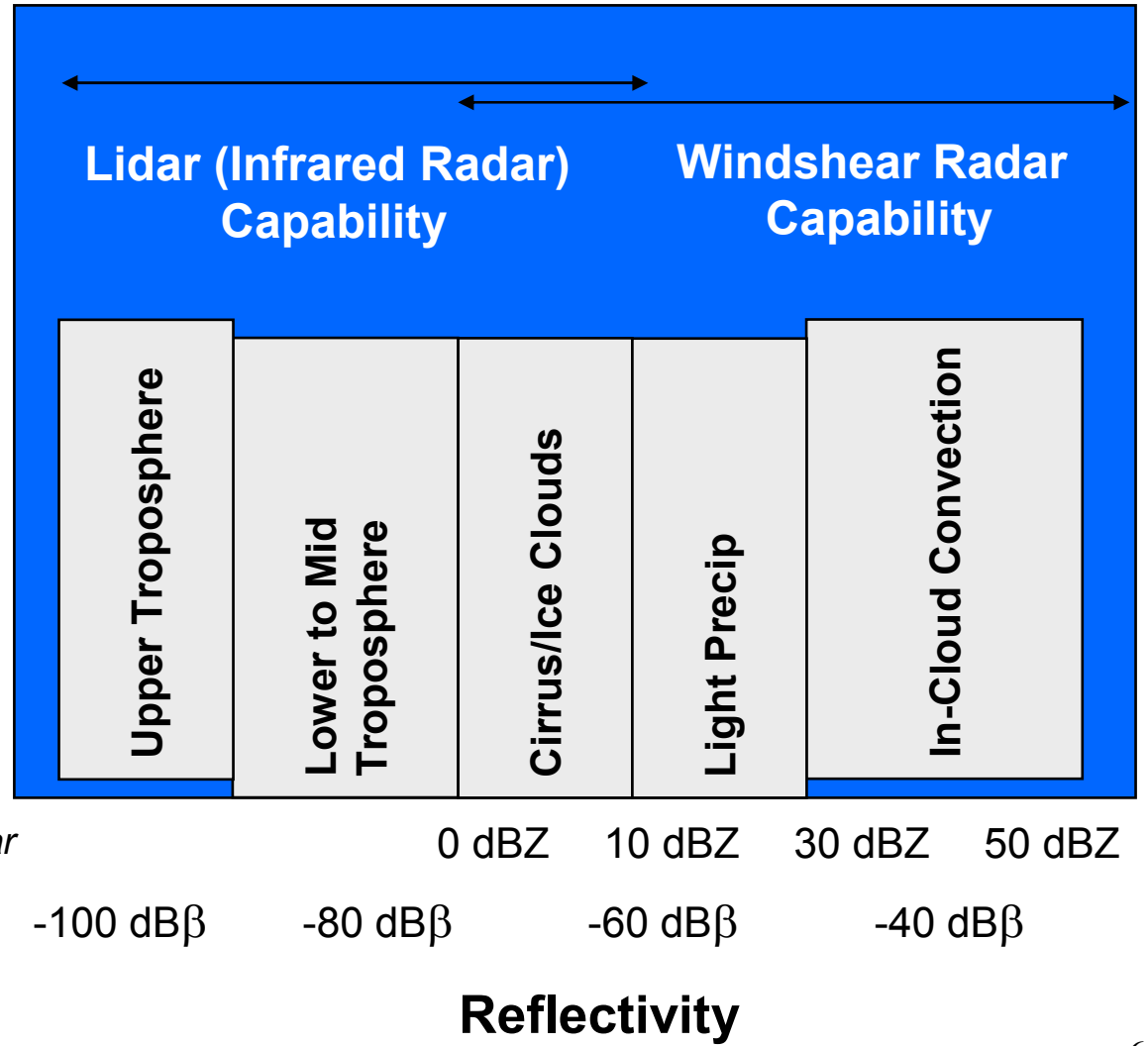
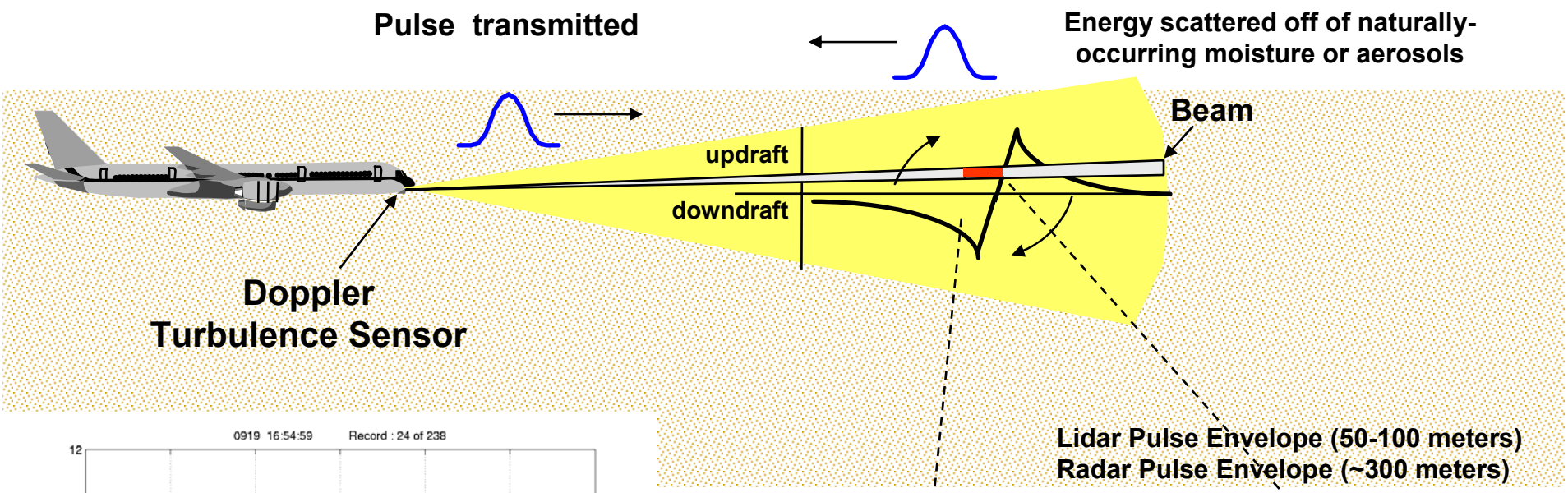
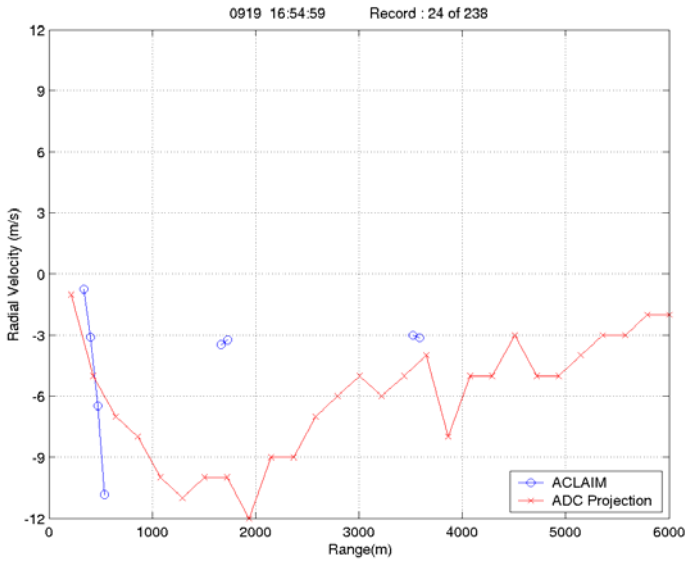
TPAWS Objective: Develop a robust detection capability that spans the full range of turbulence environments

- Convective Storms (within and as far as 40 miles away from visible clouds in clear air)
- Jet Stream (at confluence of multiple streams and near boundaries)
- Mountain and/or Gravity Wave (upward propagating from disturbances near the surface)



ACLAIM vs. DC-8 In-Situ Line-of-Site Air Velocity Measurements





Relative wind induces a Doppler frequency shift in the backscattered light; this frequency shift is detected by the sensor

DC-8 In-Situ Air Velocity presented as dot product between unit vector for lidar beam angle and true air velocity

Lidar Turbulence Detection Technology Readiness Development Needs

- Lidar needs are similar to those for microwave radar and include:
  - definition and characterization of hazard
  - hazard algorithm for quantifying the threat
  - validated algorithm(s) for using the IR radar to detect, discriminate, and quantify the threat
  - simulation test case development
  - validated system performance with properly designed field tests

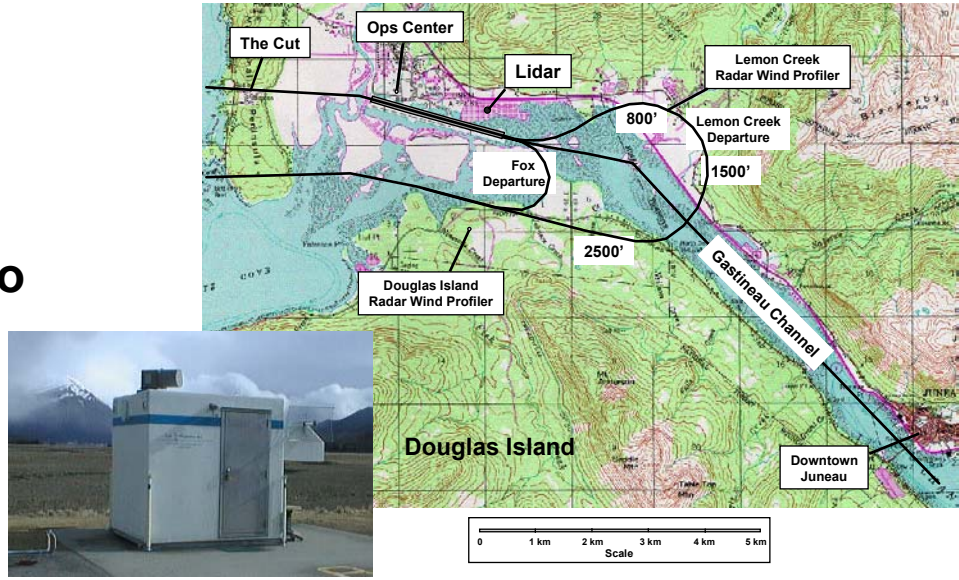
- ACLAIM flights are focused on validation of system performance under cruise conditions to the extent possible without scanning capability (no beam-scanning capability was available for the DC-8 installation)

Lidar Flight Testing: Identified Objectives and Needs

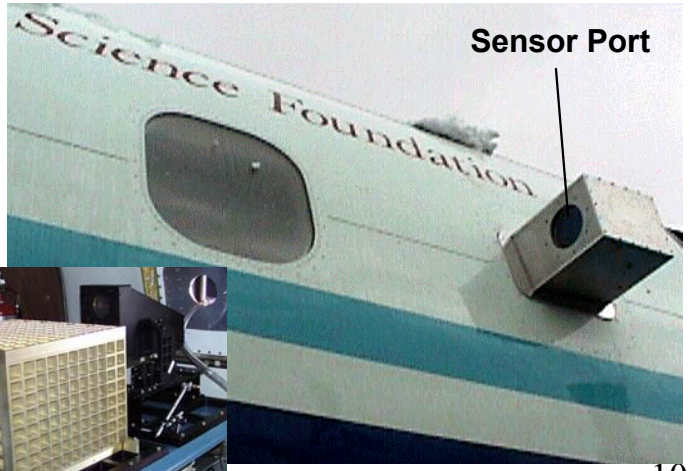
- **Flight hours at cruise altitudes**
  - identified as a major gap
  - defining turbulence signatures
- **Flight hours in moderate or stronger turbulence**
  - mid-level altitudes with focus on convective and breaking wave turbulence
  - performance envelope for onboard radar and lidar
- **Extended data sets for aerosol/turbulence correlation modeling**
- **Scanning versus single line of sight configuration**
  - scanning will enable better characterization of turbulent events
    - more direct comparison with radar for joint tests
  - include a mixture of both modes

Lidar Pre-AvSP (1998)

- **Juneau lidar deployment**
  - characterization of low altitude wind shear and turbulence
  - generated validated data sets to support development of lidar turbulence and wind shear detection algorithms



- **ACLAIM/Electra flights**
  - Detected light to moderate turbulence at ranges between 3 and 6 miles ahead
  - Penetrated turbulence to verify
  - Operated 15 hours in a variety of conditions from ground to 25kft



Lidar Background Summary

- **Emphasis areas**
  - flight testing
  - algorithm development and associated performance analyses
- **Flight tests accomplished CY98-03**
  - NASA ACLAIM Electra flights
  - industry-funded B-720 flights
  - DC-8 flights piggy-back on CAMEX-4 and KAMP (FY01)
  - DC-8 piggy-back with Cold Land Processes (CLPX) and Coastal Eddy Experiments
- **Algorithm work highly leveraged**
  - NCAR and CTI developments
  - synergy with radar work (NCAR & RTI)
- **Parallel industry program to develop a clear air turbulence product**
  - focus is on cost reduction and reliability improvement

ACLAIM Overview

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- CLPX and CAMEX-4 piggyback
- 3 rack installation
  - High rack, Low rack, Chiller
  - 2 seats at high rack
- Integrated AFRL/NASA lidar system hardware with Class IIIb laser
- Fixed azimuth (~1.65º) and hand-cranked elevation periscope installed at DC-8 Flight Station 1015
- Several Instrument Check Flights (ICF) and 30 research flights
- ~163 hours of flight time / ~2 hours dedicated time
- ~330 GB of flight data

Lidar Transceiver and Data Acquisition and Control System

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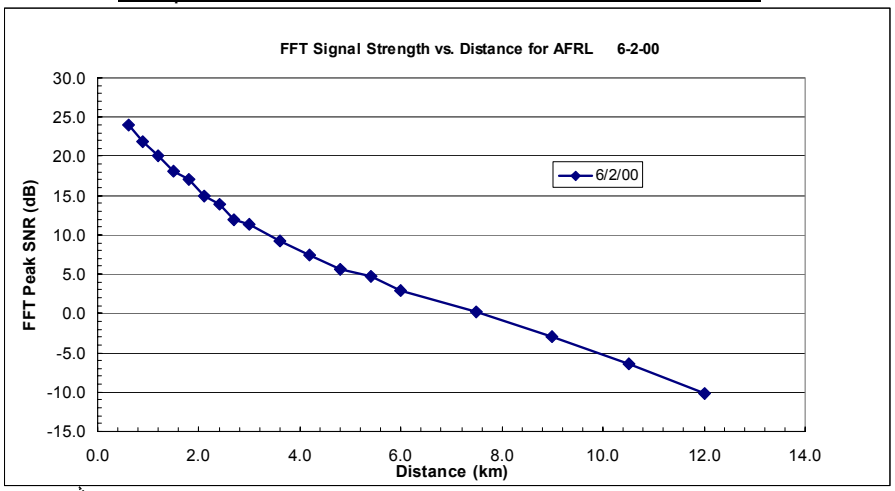
- **AFRL Transceiver Specs after Fall 02 tune-up at CTI**
  - 2.0125 μm wavelength, 9.3 mJ (out of telescope), 650 nsec pulse duration, 100 Hz PRF
  - 8 cm beam diameter, 10 cm aperture, internal telescope focused at 2.5 km
  - 14% system efficiency
  - horizontal path data show range performance to 10-12 km (Colorado data)
- **NASA Data Acquisition and Control System**
  - 50 m/sec analog bandpass for Doppler velocity
  - Bandpass centered on DC-8-supplied (1Hz) True Air Speed component parallel to lidar direction
  - 90m range gates, 1sec averaging, data collection range selected as 12km
  - Flight data file size set to 4min to expedite storage and analysis

Sample Data Collected for Horizontal Path In Colorado



NASA/ACLAIM System

CAMEX-4 ACLAIM Flights

ACLAIM CAMEX-4								
Flight	DC-8 Flight#	Date	Flight Duration (hr)	Flight Type	Target	Other A/C	Data (GB)	Data (CDs)
ICF1	01-04-03	8/3/2001	2	ICF		-	2.0	3
ICF2	01-04-04	8/8/2001	3	ICF		-	2.5	5
1	01-04-06	8/18/2001	5		Andros Island	ER2	7.6	15
2	01-04-07	8/20/2001	8	CAMEX	Chantal	ER2	8.9	17
3	01-04-08	8/25/2001	2	ICF	buoy off Cape Kennedy	-	5.7	10
4	01-04-09	9/3/2001	5	KAMP	Keys	ER2, P3	8.8	16
5	01-04-10	9/6/2001	2	KAMP	Keys / TRM		7.1	13
6	01-04-11	9/7/2001	5	KAMP	Tampa - Gulf	ER2	10.9	20
7	01-04-12	9/9/2001	5	KAMP	Keys		7.4	20
8	01-04-13	9/10/2001	8.5	CAMEX	Erin		18.2	35
9	01-04-14	9/15/2001	6.5	CAMEX	Gabrielle		16.0	29
10	01-04-15	9/19/2001	5	KAMP	Keys		12.0	22
11	01-04-16	9/22/2001	8	CAMEX	Humberto	ER2, P3	20.1	37
12	01-04-17	9/23/2001	8	CAMEX	Humberto	ER2, P3 +3	19.7	36
13	01-04-18	9/24/2001	8.25	CAMEX	Humberto	ER2, P3	21.9	40
			81.3				168.9	318

CLPX and Coastal Eddy ACLAIM Flights

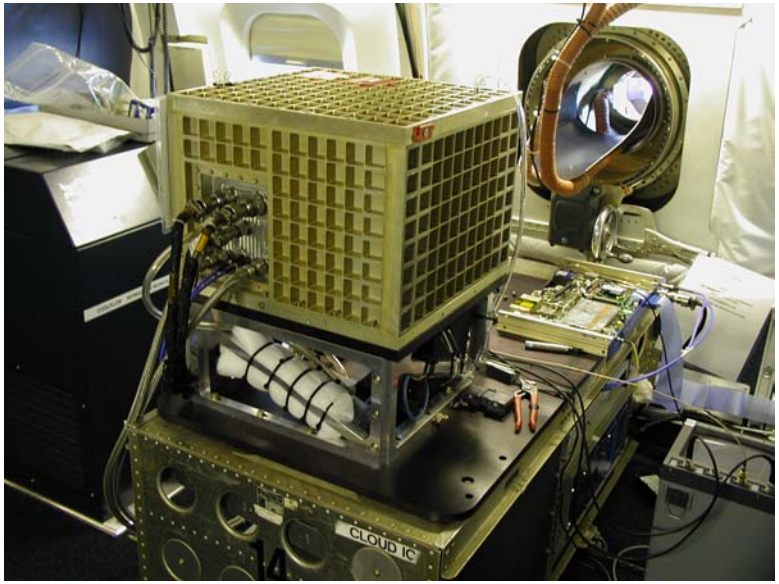
	ACLAIM CLPX/Coastal Eddies				
Flight	DC-8 Flight#	Start Date	Takeoff	Landing	Flight Duration (hours)
Experimental Flight 1	030302	3/12/2003	21:05:06	0:06:10	3
Experimental Flight 2	030303	3/17/2003	15:25:XX	19:13:59	4
Experimental Flight 3	030304	3/20/2003	15:38:04	16:40:23	1
Transit Flight	030305	3/24/2003	16:58:26	21:34:56	4.5
CLPX Flight 1	030306	3/25/2003	18:22:43	1:33:01	7
CLPX Flight 2	030307	3/28/2003	18:20:XX	1:03:21	6.5
CLPX Flight 3	030308	3/30/2003	18:26:23	1:02:04	6.5
CLPX Flight 4/transit	030309	3/31/2003	~17:00	23:03:08	6
Coastal Eddy 1	030310	4/14/2003	15:55:45	18:26:25	2.5
Coastal Eddy 2	030311	4/15/2003	19:15:58	22:36:44	3.25
Coastal Eddy 3	030312	4/16/2003	15:05:39	21:17:30	5.25
Coastal Eddy 4	030313	4/18/2003	15:59:33	~21:40	5.5
Coastal Eddy 5	030314	4/19/2003	15:07:58	21:24:25	6
Coastal Eddy 6	030315	4/21/2003	15:06:44	22:44:54	7.5
Coastal Eddy 7 Search & Rescue	030316	4/22/2003	0:54:14	6:20:25	6.5
* ACLAIM Dedicated	030317	4/23/2003	20:00:05	22:06:55	2
Coastal Eddy 8*	030318	4/28/2003	14:35:40	21:09:22	6.5
Totals					83.5

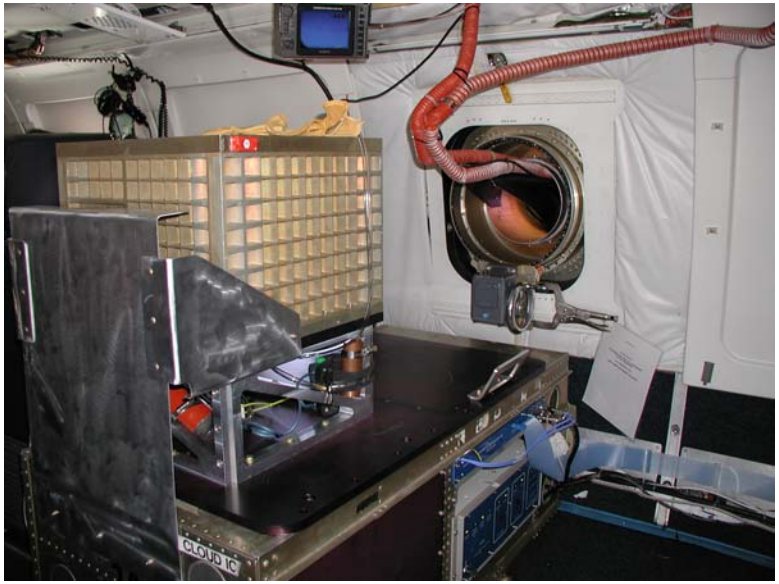
NASA DC-8 Facility with Lidar Periscope Installed

ACLAIM Installation – High Rack Operator-Side

ACLAIM Installation – High Rack Forward-Side

ACLAIM Installation – Low Rack





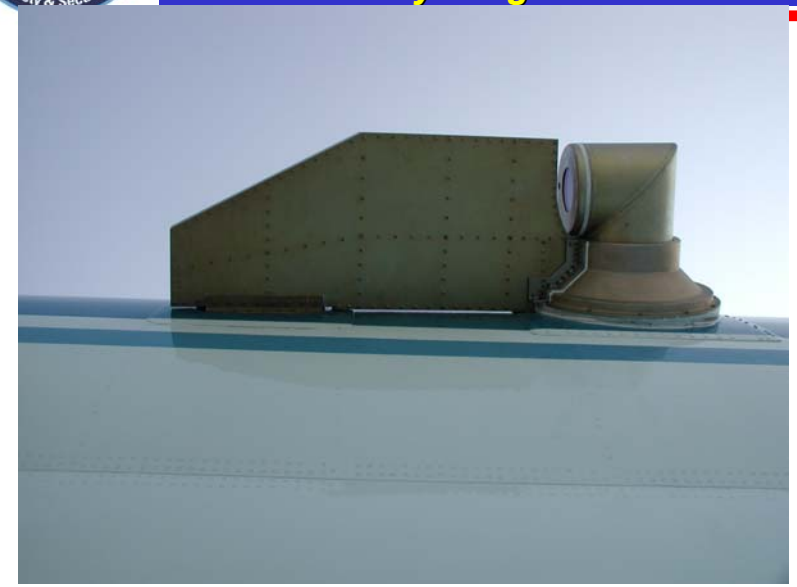
ACLAIM Installation – Chiller

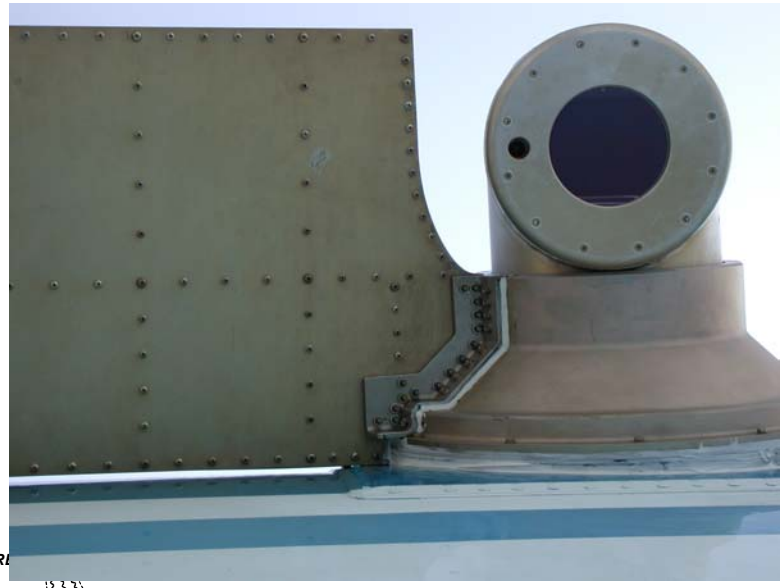
Note:

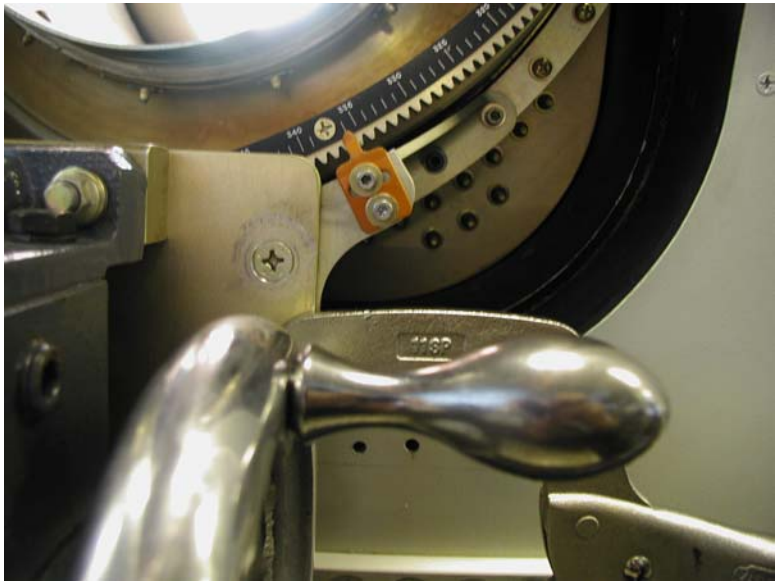
Oversize COTS recirculating iso-thermal bath used for cost savings and breadboard/brassboard flexibility.

Current generation systems have replaced this with an internal recirculating loop with thermo-electric temperature control (similar to those used in PC's with liquid-cooled CPU's).

ACLAIM Installation – Hand-Operated Periscope for Setting Elevation Angle

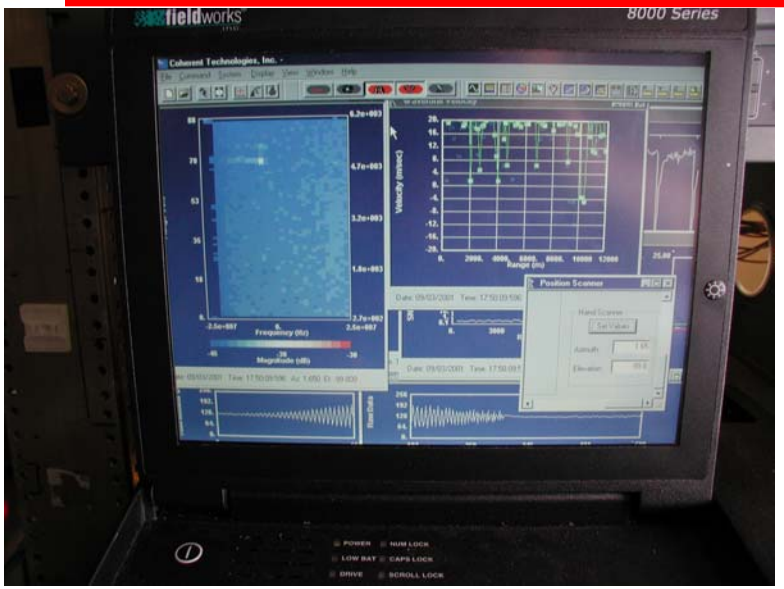


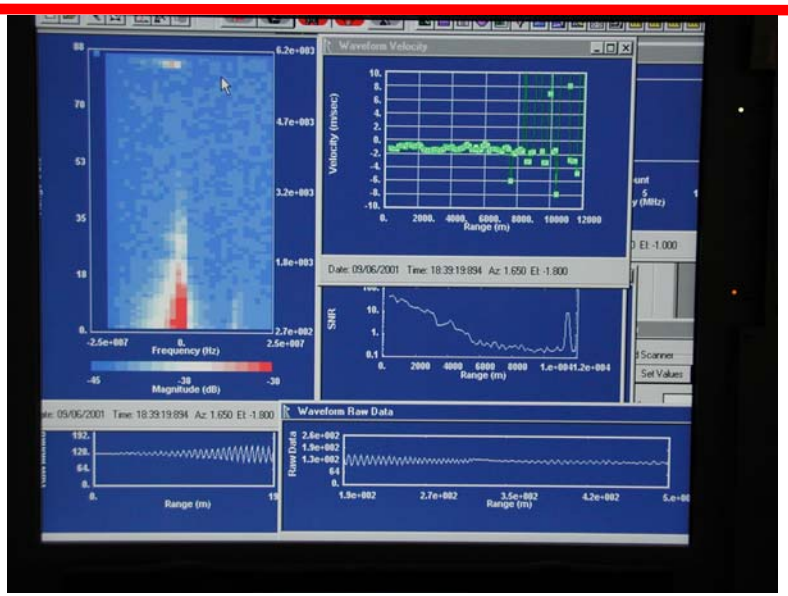


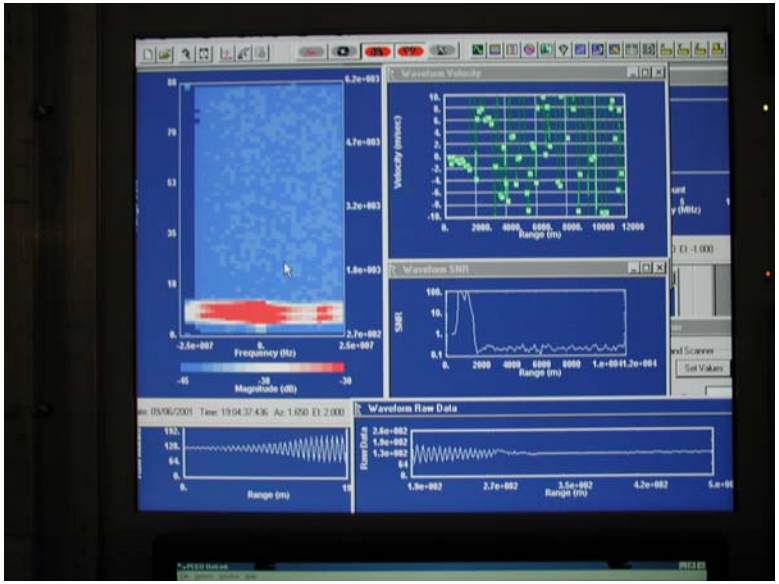


ACLAIM Installation – Situation Awareness Using Camera Mounted in Lidar Periscope

ACLAIM Operator's Screen Sample







Sample Doppler Spectrum from ACLAIM/Electra

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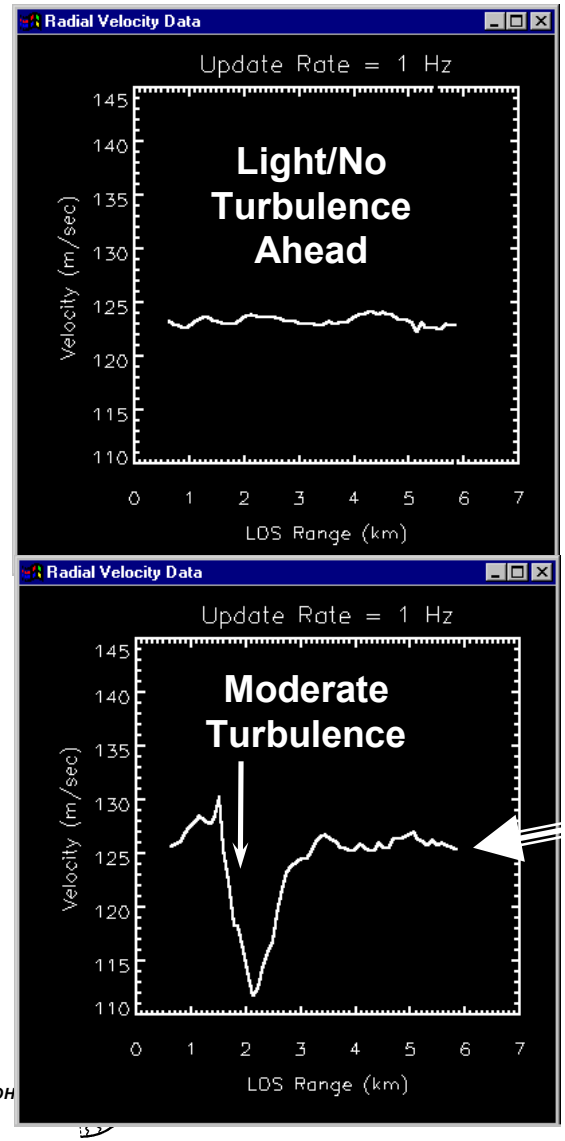
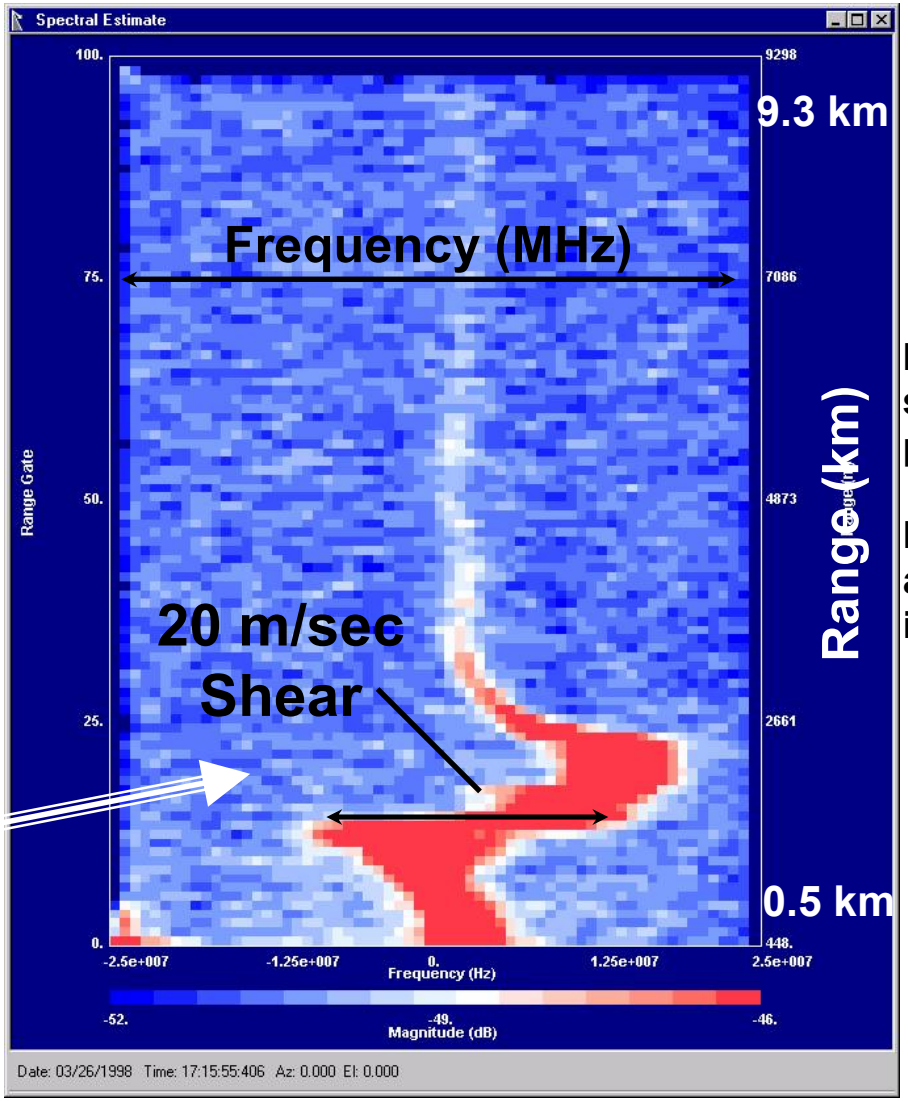
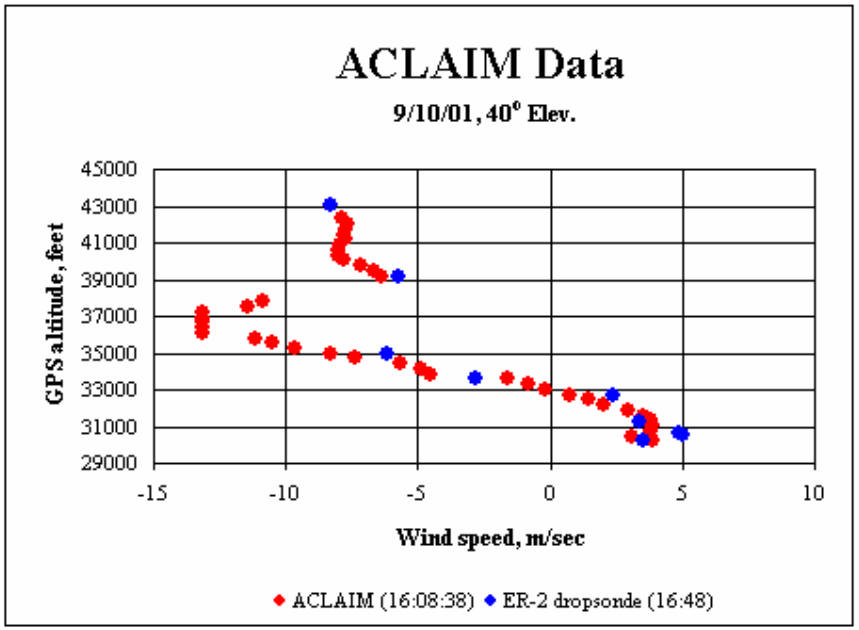


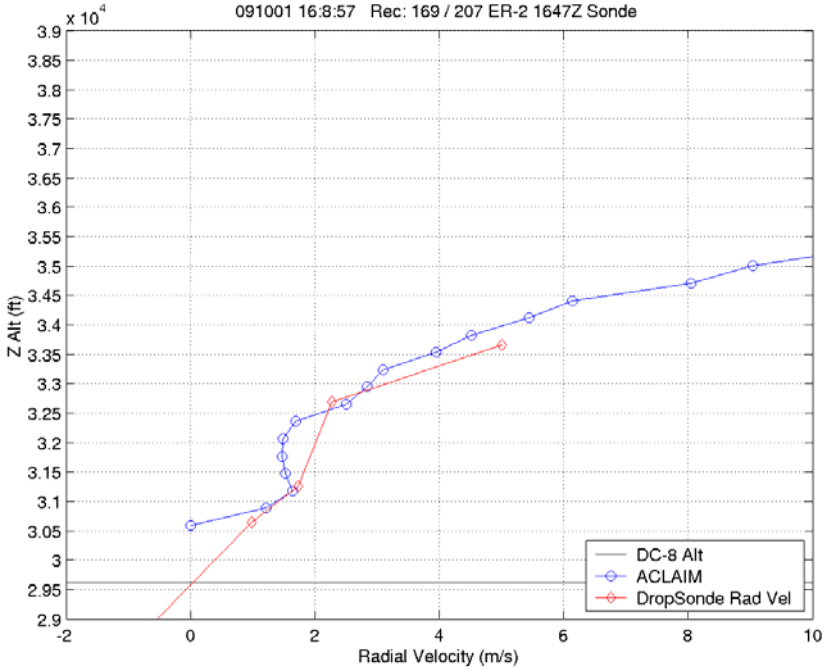


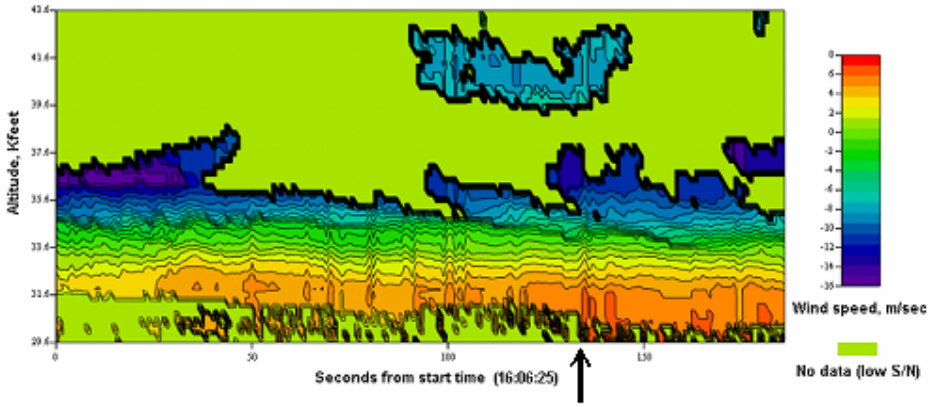
Isolated moderate to severe turbulence patch ahead

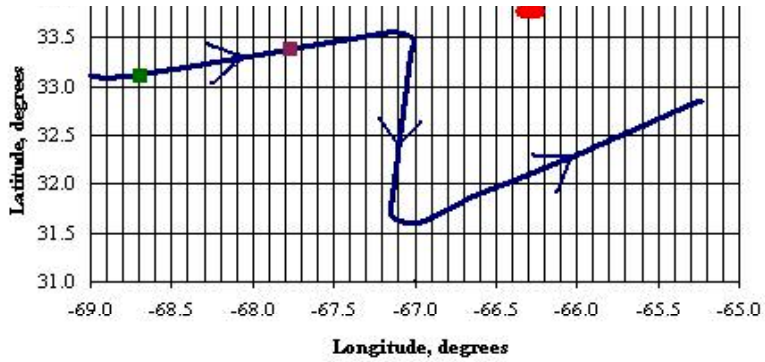
Detected turbulence and later penetrated it for confirmation

ACLAIM vs Dropsonde Windshear September 10, 2001 Comparison









CLPX and Coastal Eddy Data Discussion

Four flights:

April 23, 2003	Dedicated ACLAIM flight Mountain wave
April 28, 2003	Variation in SNR
April 28, 2003	Mountain wave Rotor Turbulence
March 17, 2003	Strong Turbulence

April 23, 2003 ACLAIM Mountain Wave Dedicated Flight

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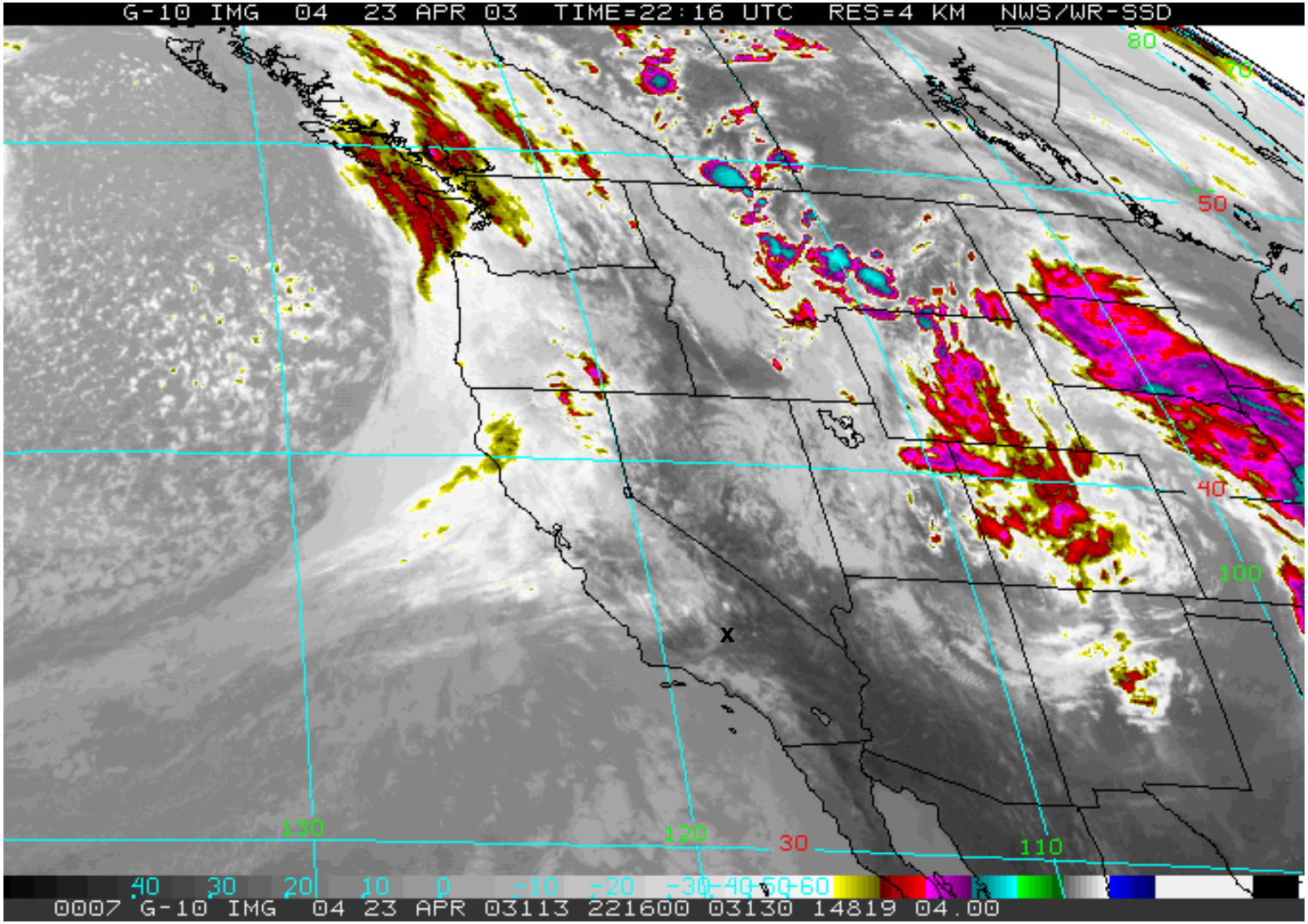
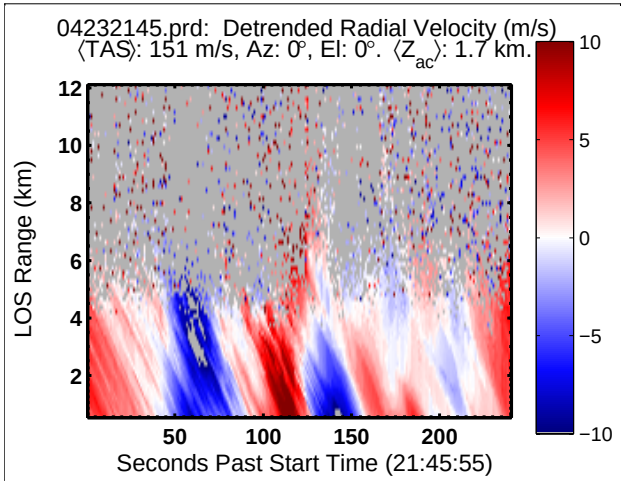
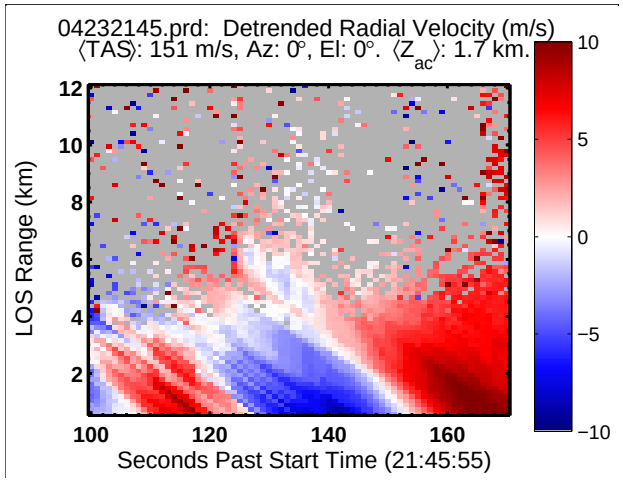


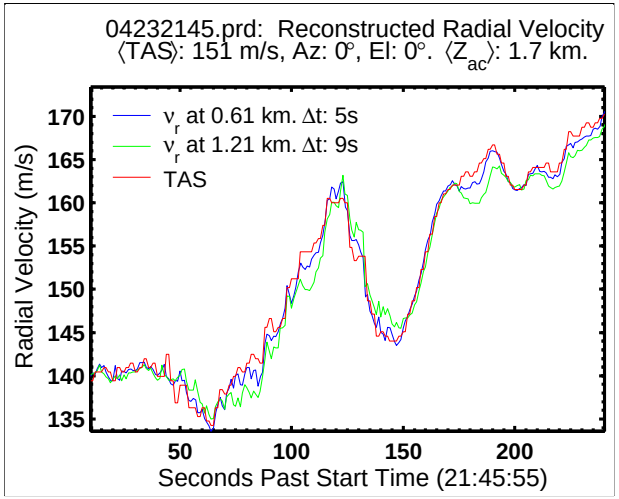
April 23, 2003 ACLAIM Mountain Wave Dedicated Flight

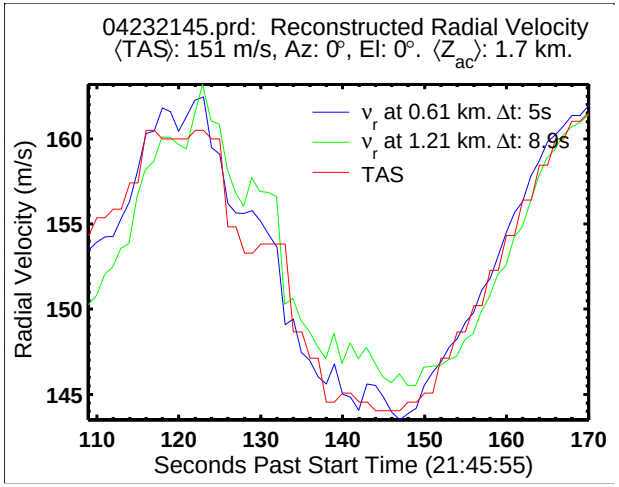
Doppler Shift



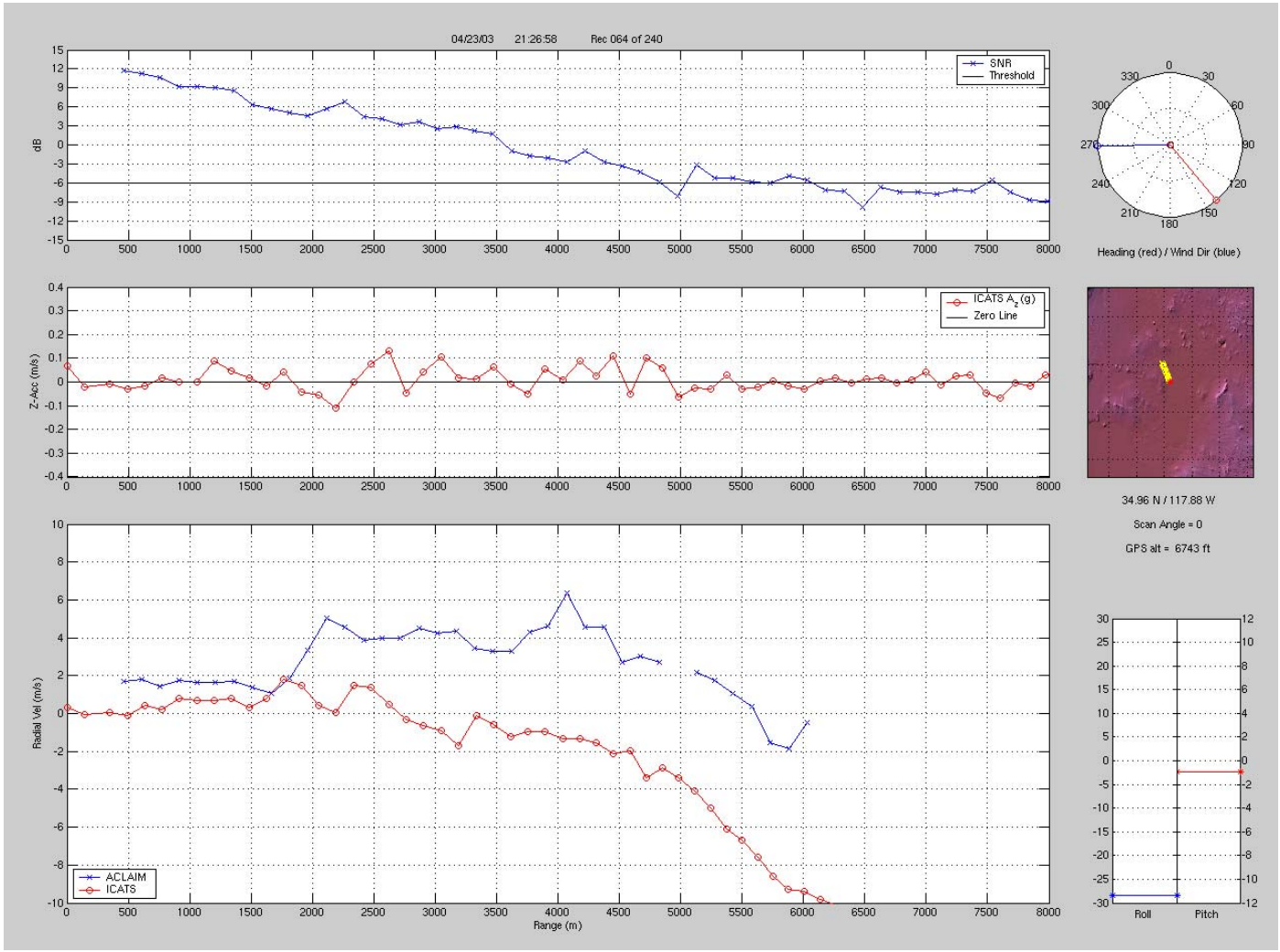


1 Hz Data

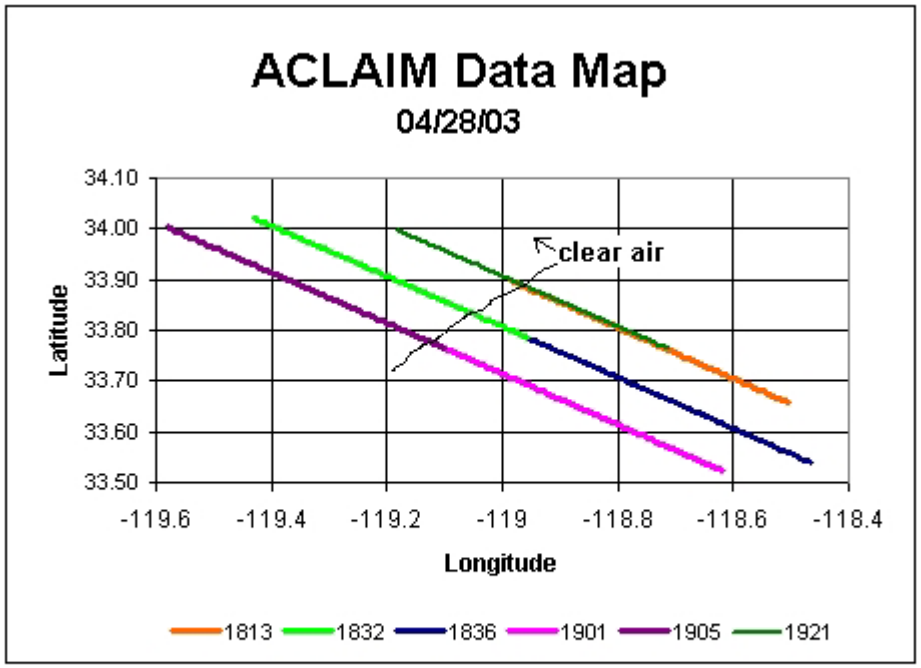




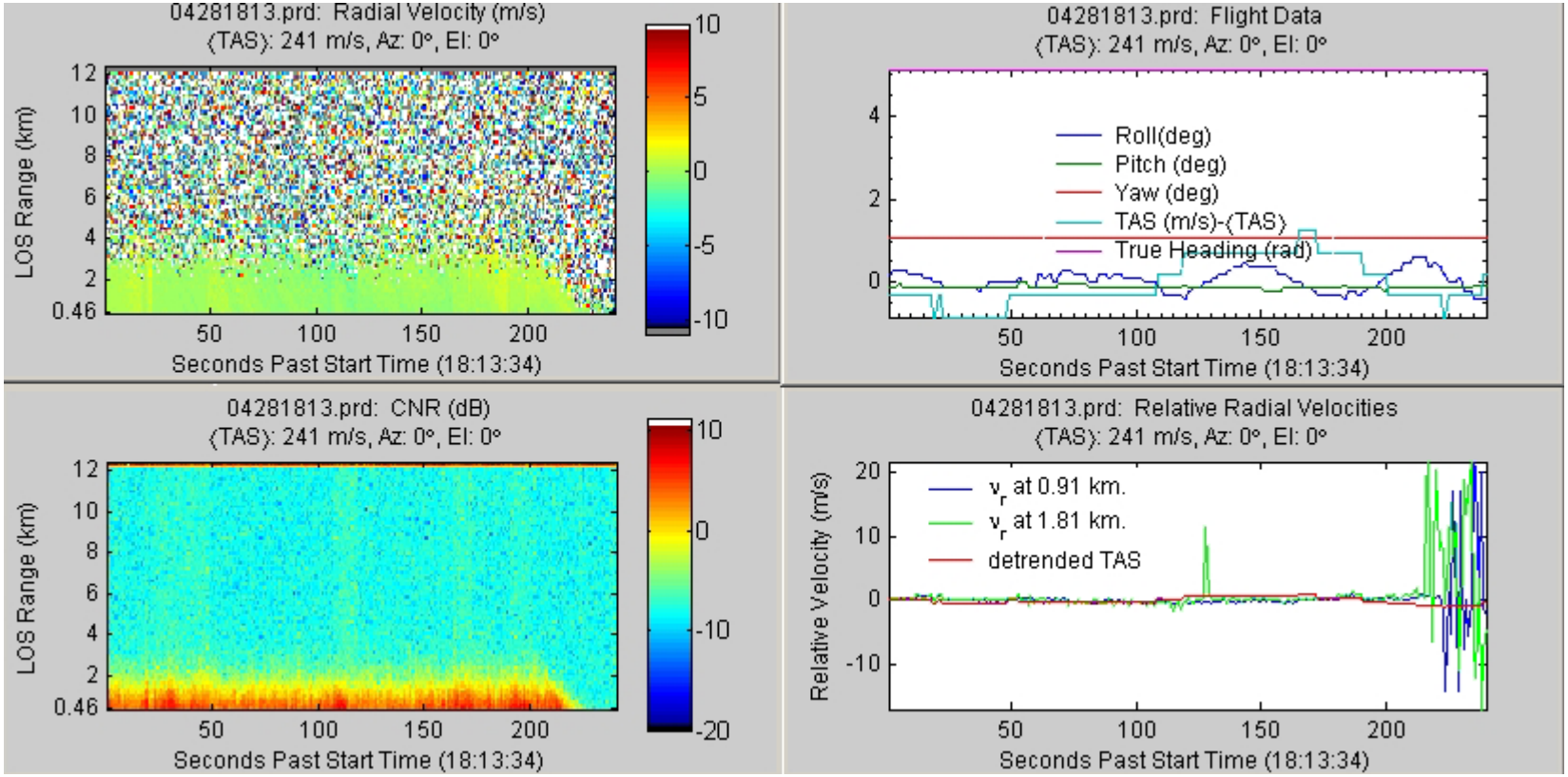
April 23, 2003 ACLAIM Mountain Wave Dedicated Flight



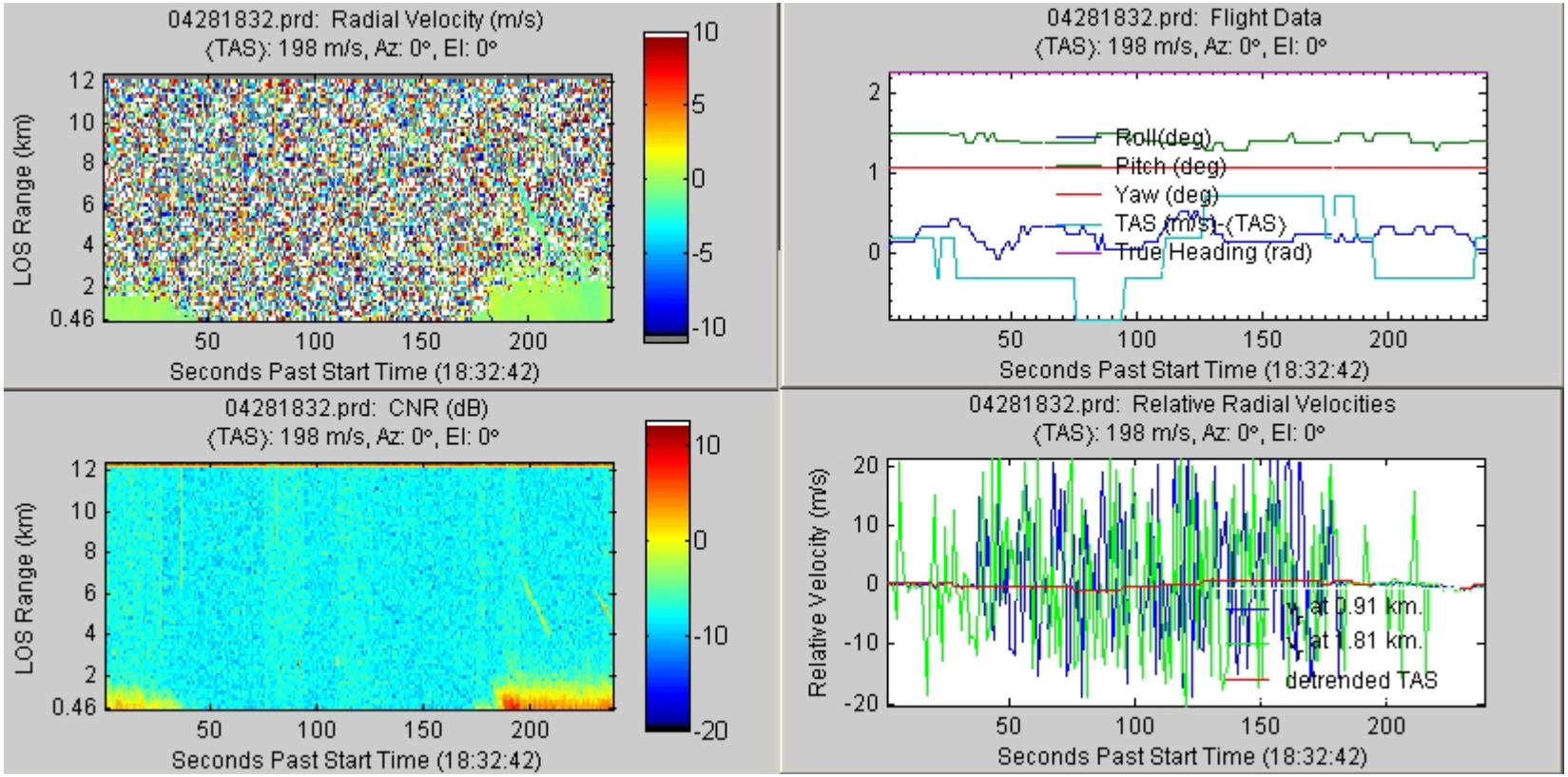
April 28, 2003 Variation in SNR



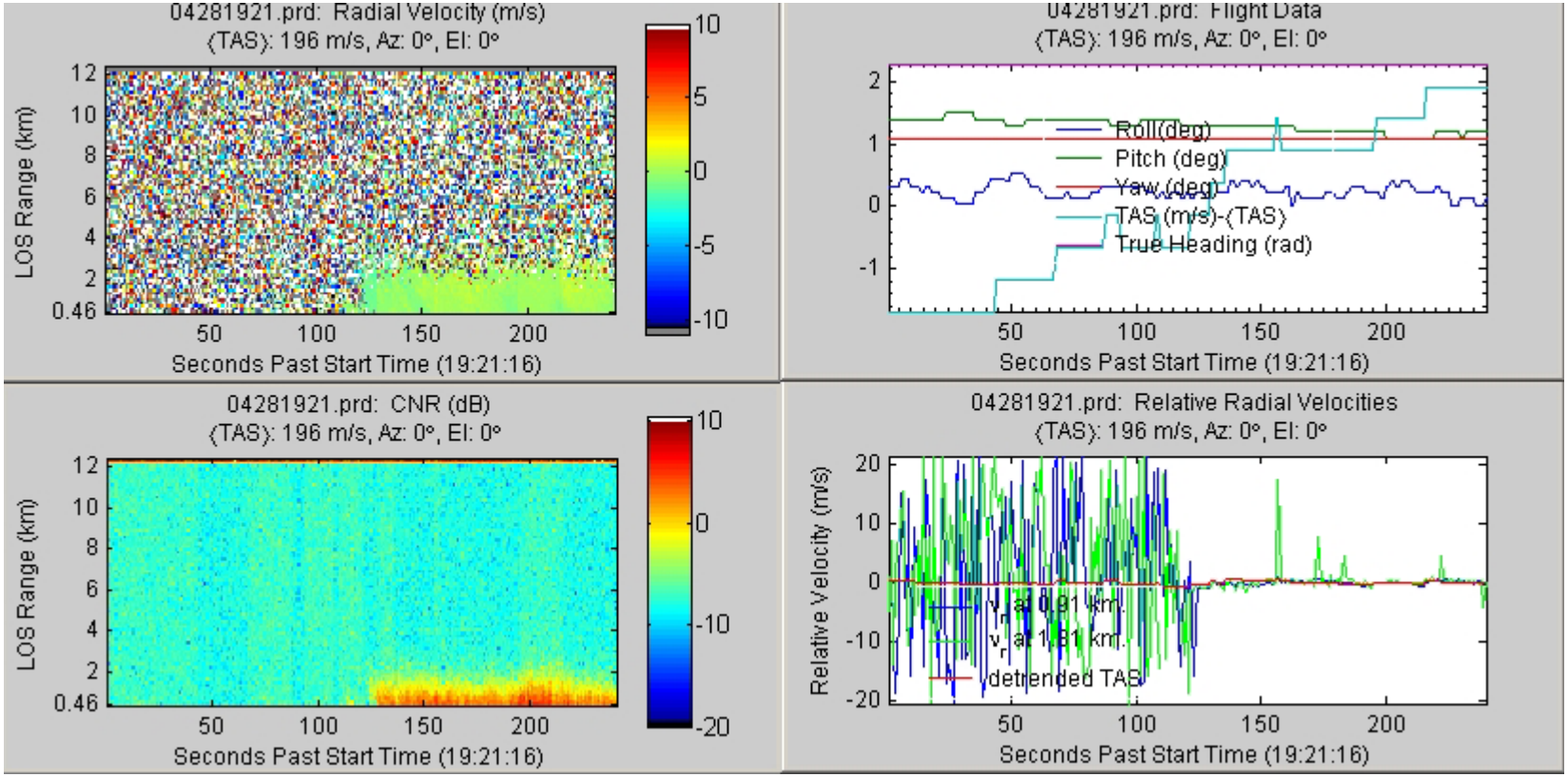
April 28, 2003 Variation in SNR



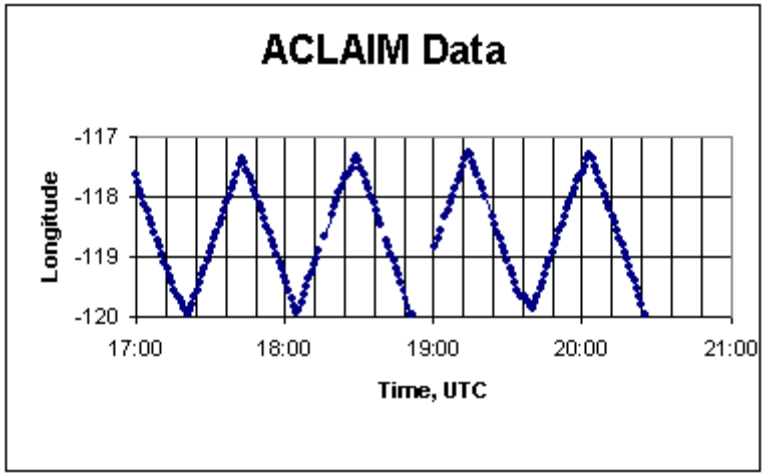
April 28, 2003 Variation in SNR

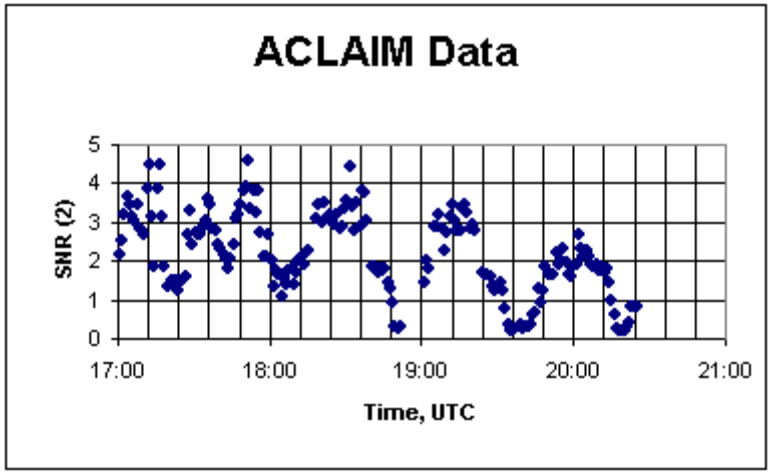


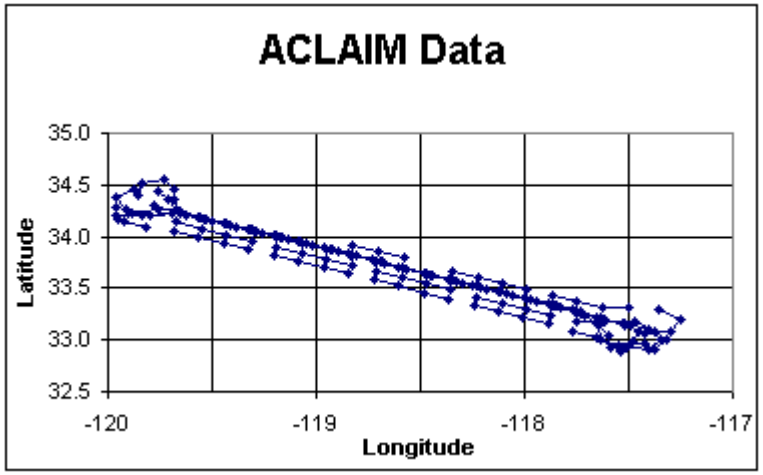
April 28, 2003 Variation in SNR



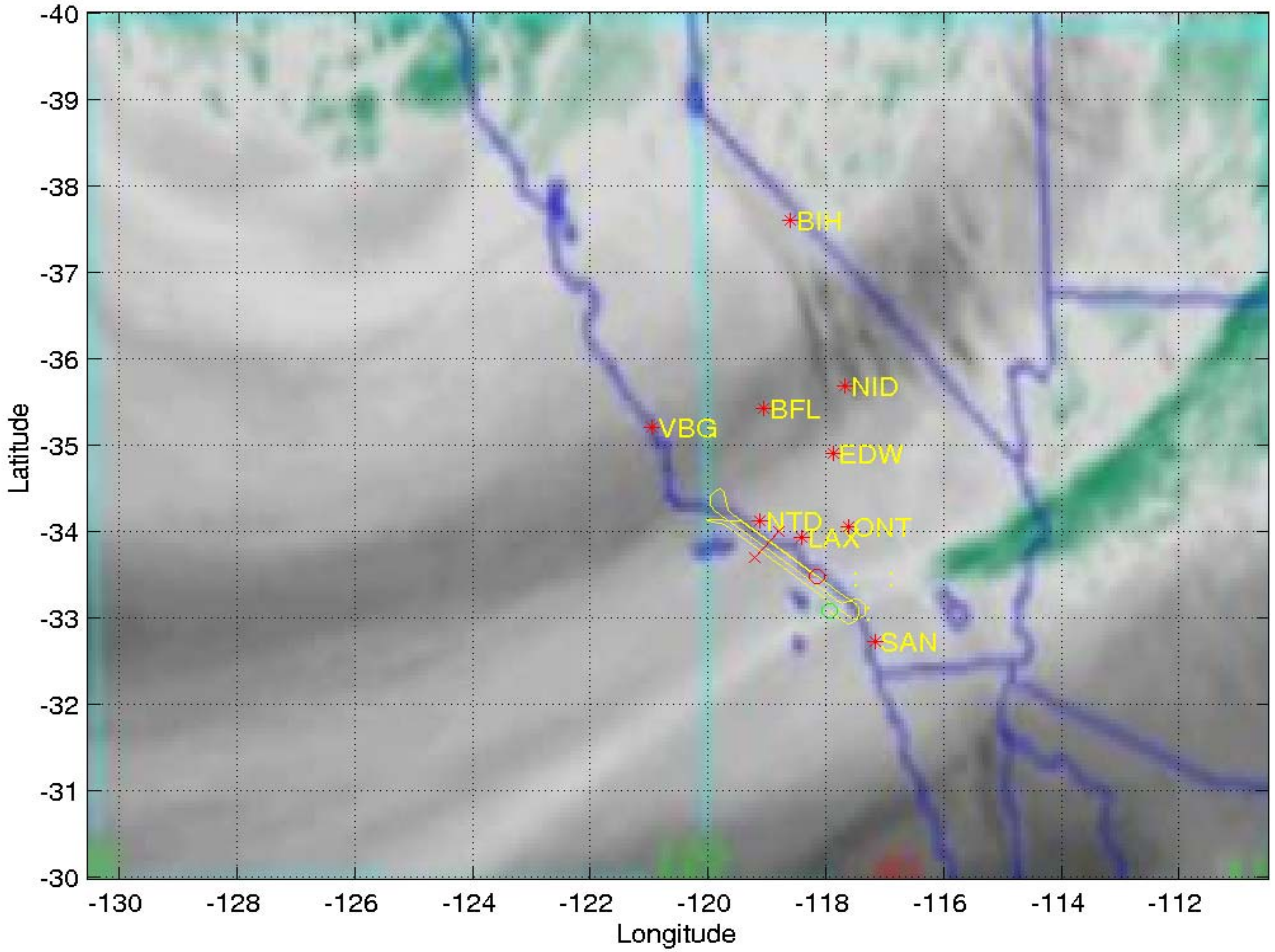
April 28, 2003 Variation in SNR





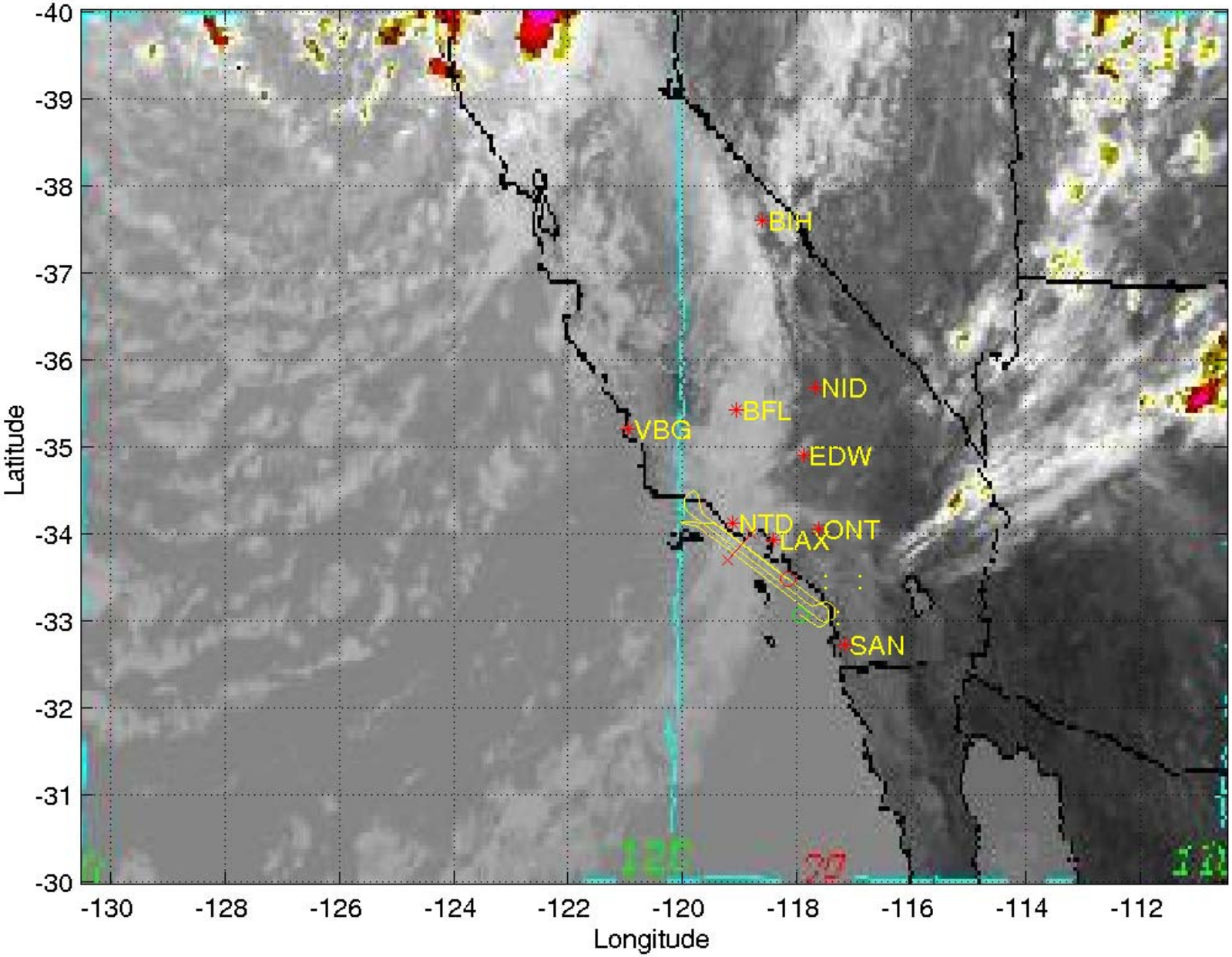


April 28, 2003 Variation in SNR and Mountain Wave Rotor Turbulence



Flight track w/ WV overlay for the April 28 case. Time start = 18:00:00, time stop = 19:30:00

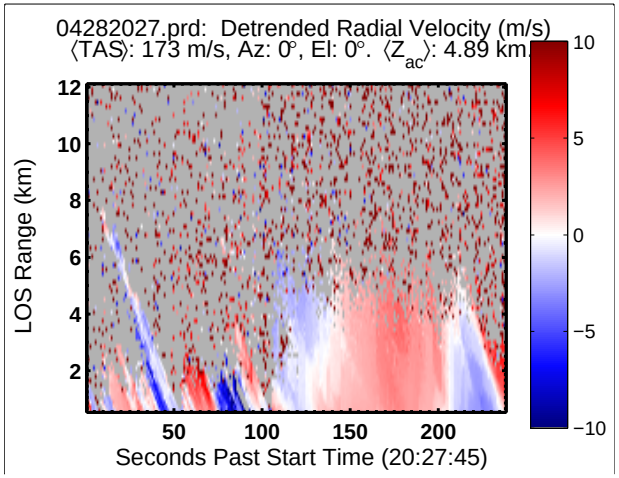
April 28, 2003 Mountain Wave Rotor Turbulence

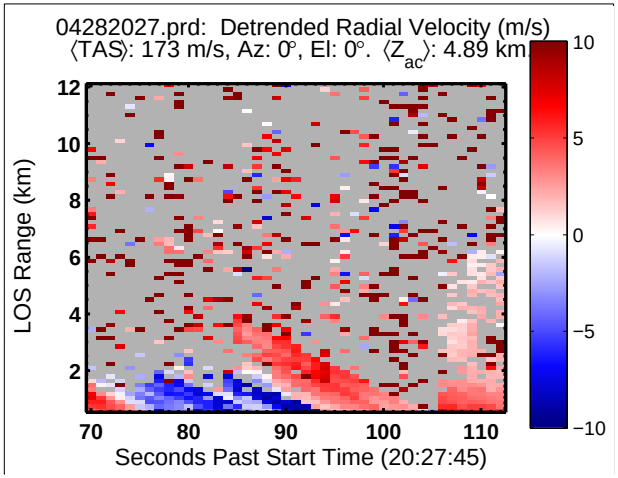


Flight track w/ IR overlay for the April 28 case. Time start = 18:00:00, time stop = 19:30:00

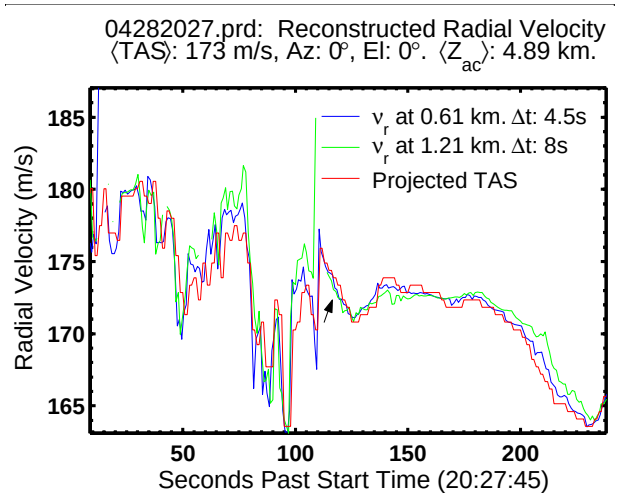
April 28, 2003 Mountain Wave Rotor Turbulence

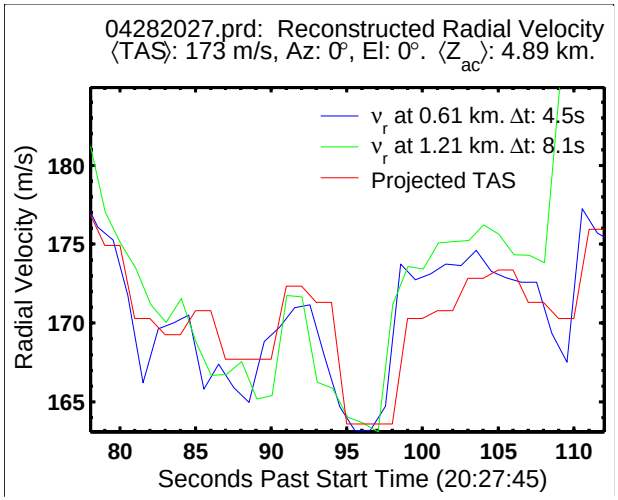
Doppler Shift



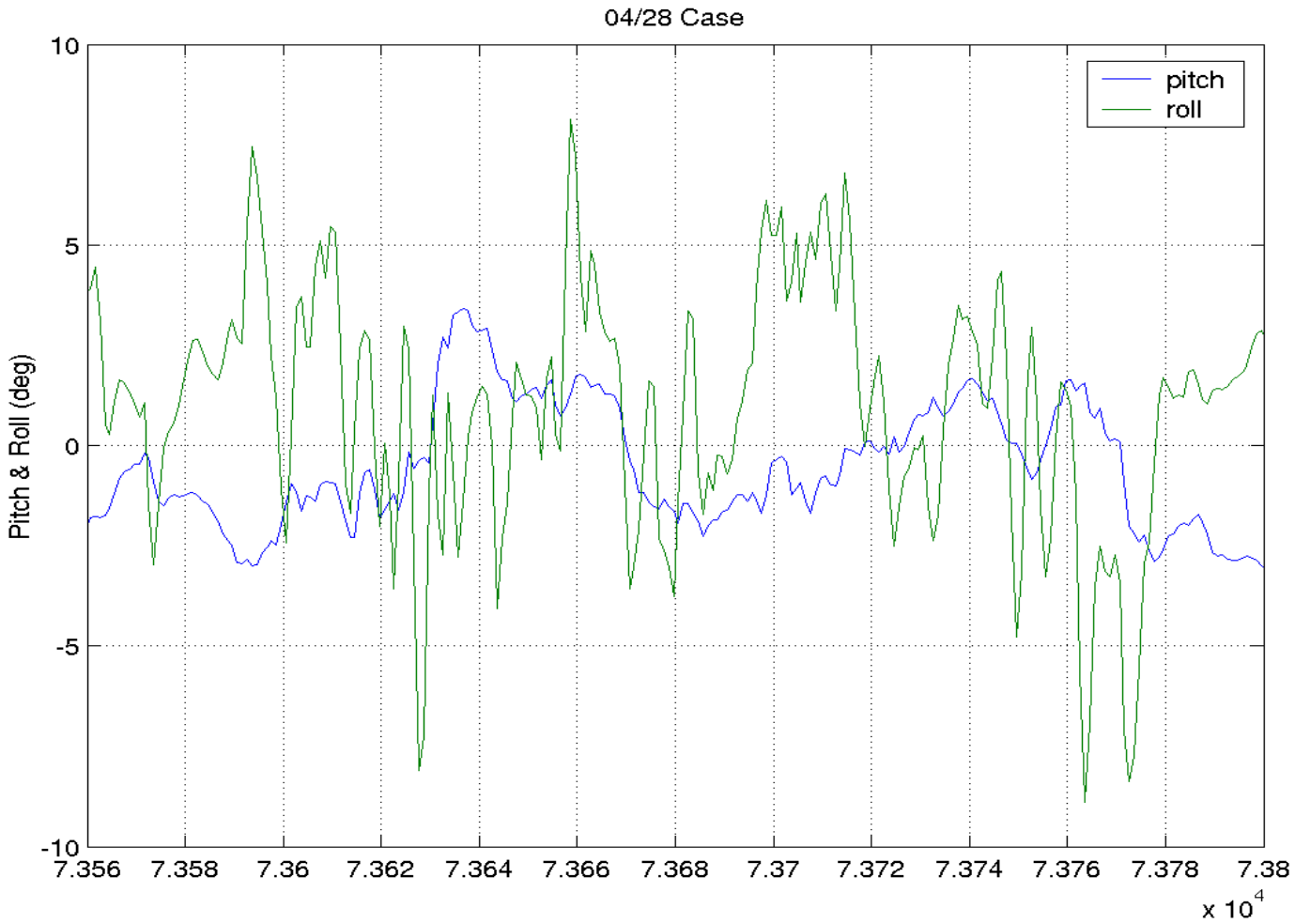


1 Hz Data



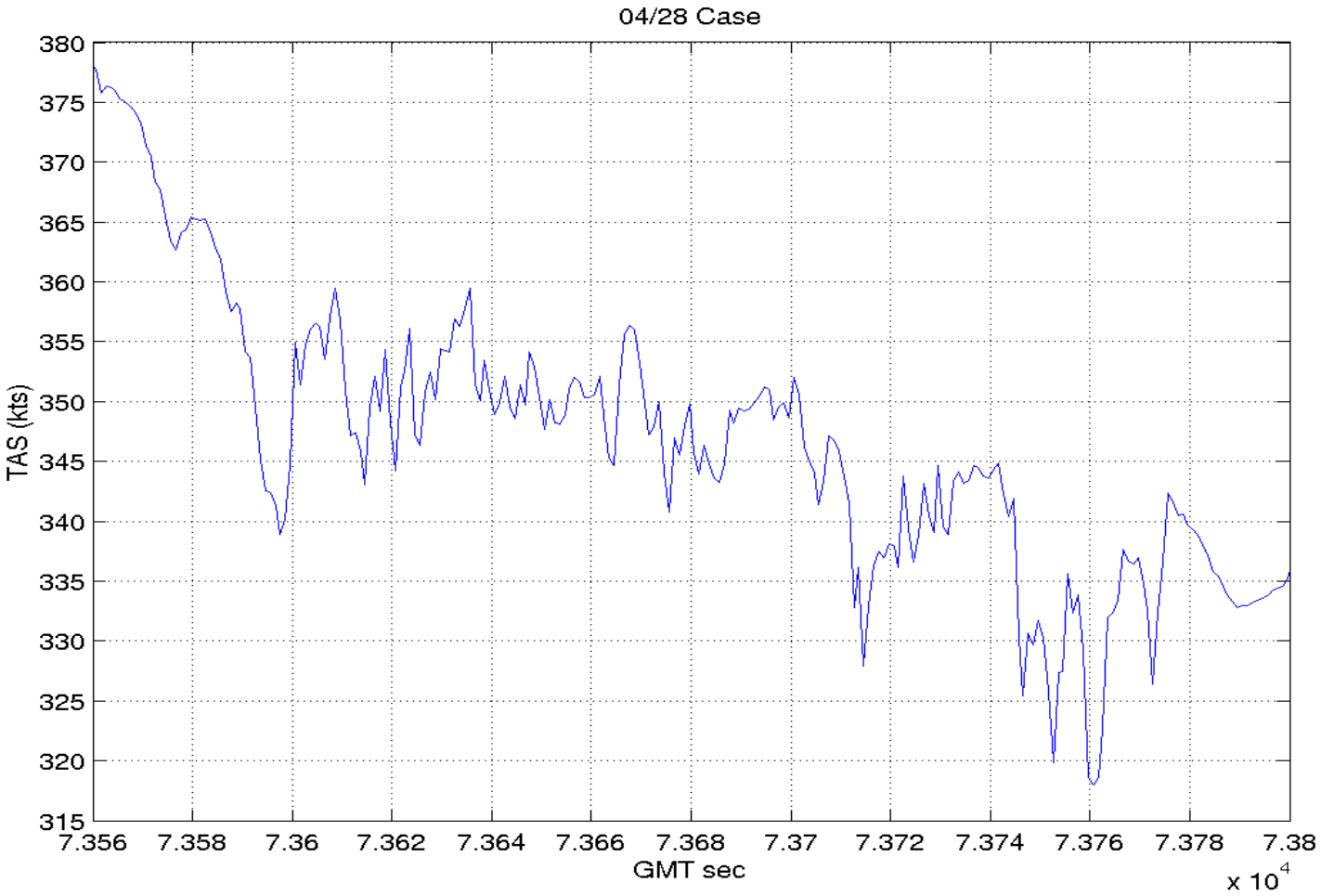


April 28, 2003 Mountain Wave Rotor Turbulence



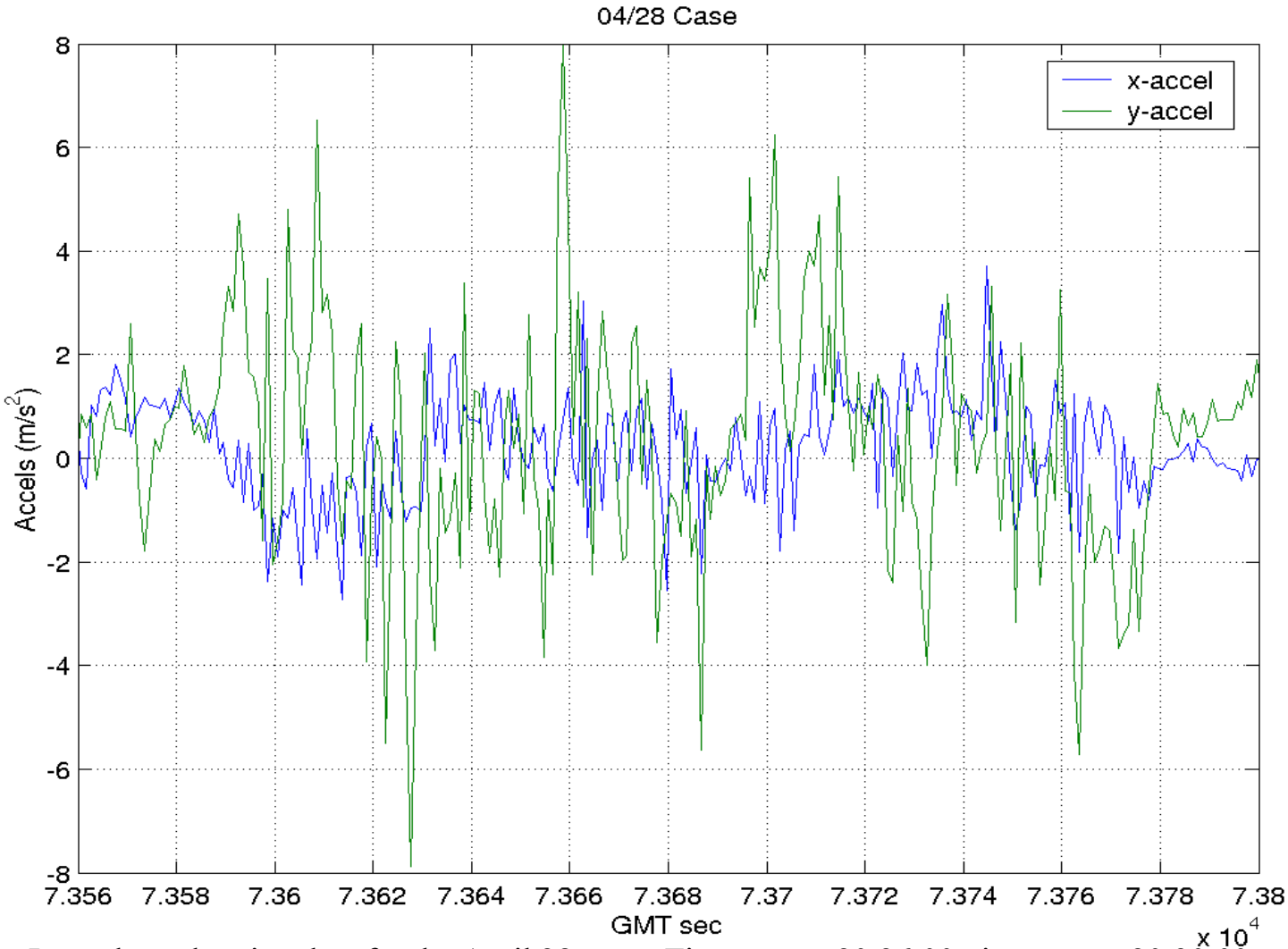
Pitch & roll data for the April 28 case. Time start = 20:26:00, time stop = 20:30:00

April 28, 2003 Mountain Wave Rotor Turbulence



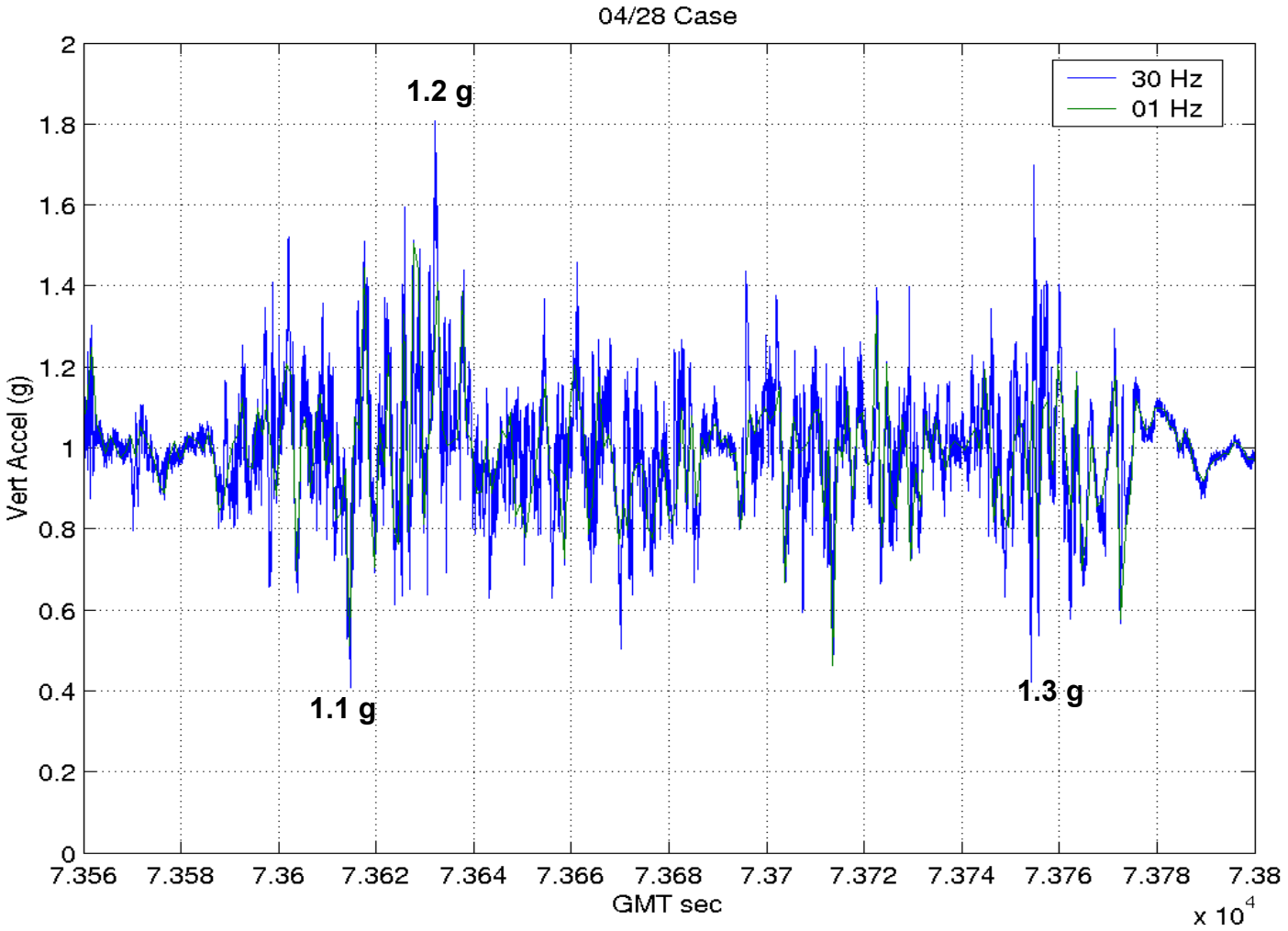
TAS data for the April 28 case. Time start = 20:26:00, time stop = 20:30:00

April 28, 2003 Mountain Wave Rotor Turbulence



Lateral acceleration data for the April 28 case. Time start = 20:26:00, time stop = 20:30:00

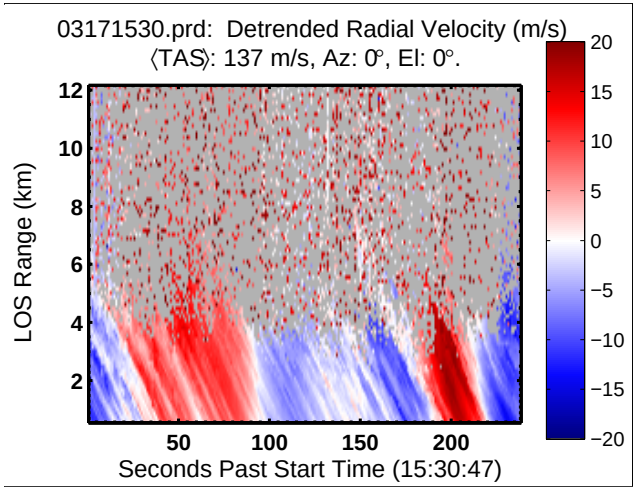
April 28, 2003 Mountain Wave Rotor Turbulence

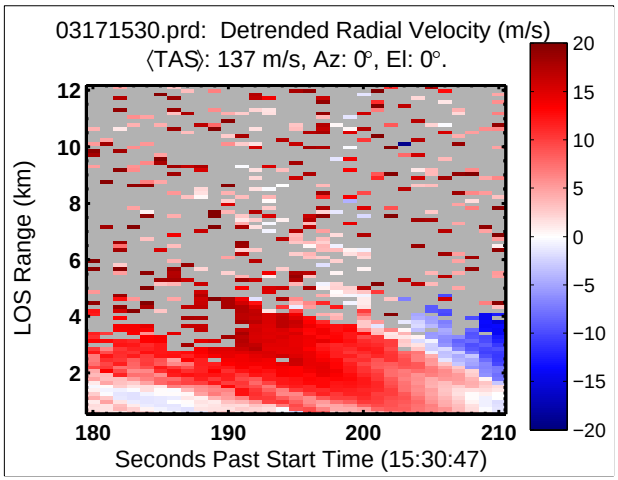


Vertical acceleration data for the April 28 case. Time start = 20:26:00, time stop = 20:30:00

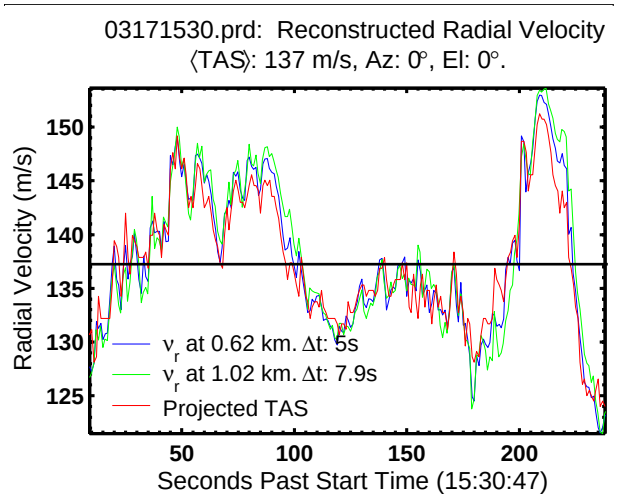
March 17, 2003 Strong Turbulence

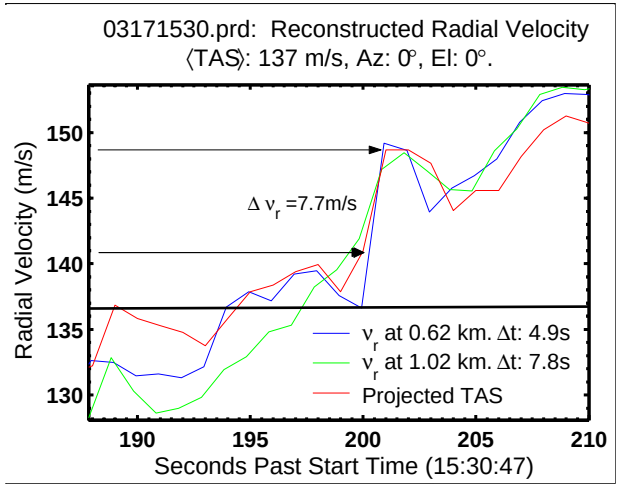
Doppler Shift

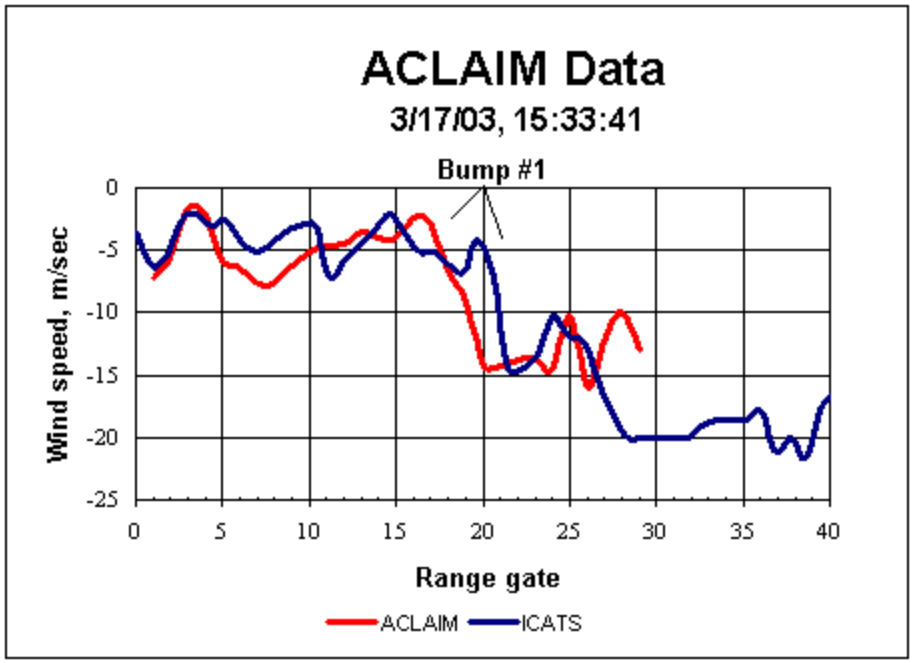


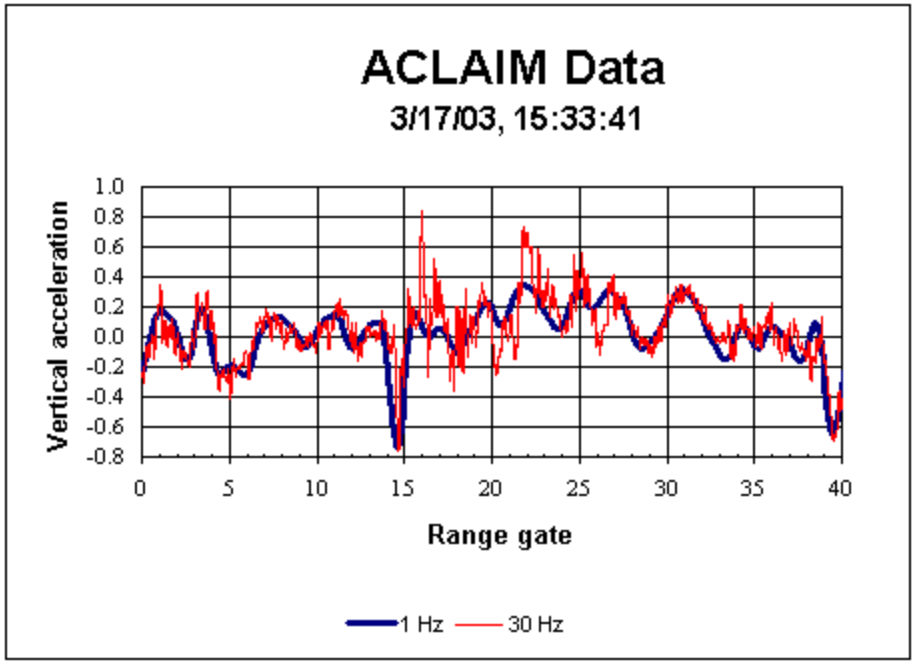


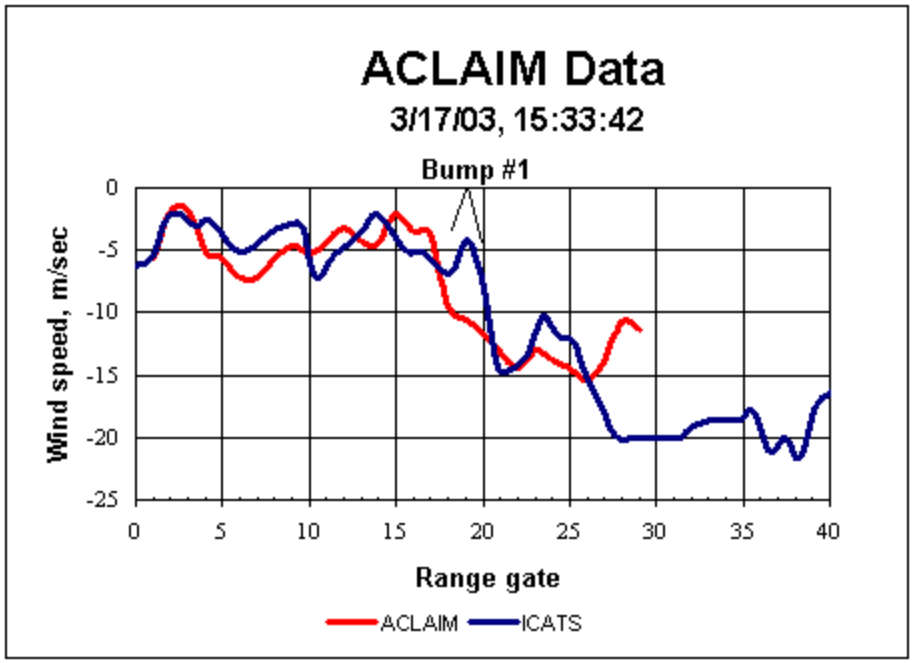
1 Hz Data

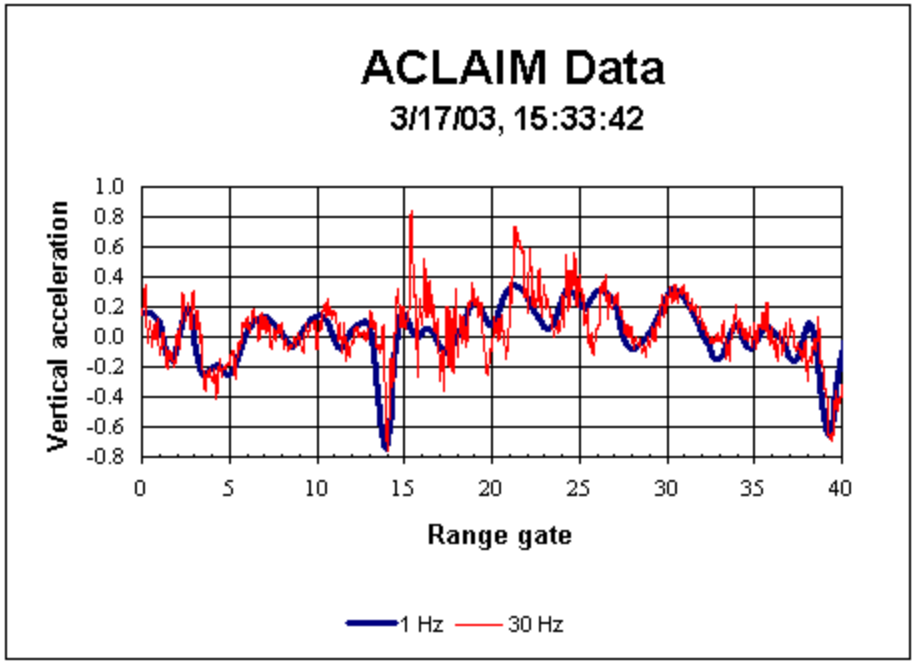


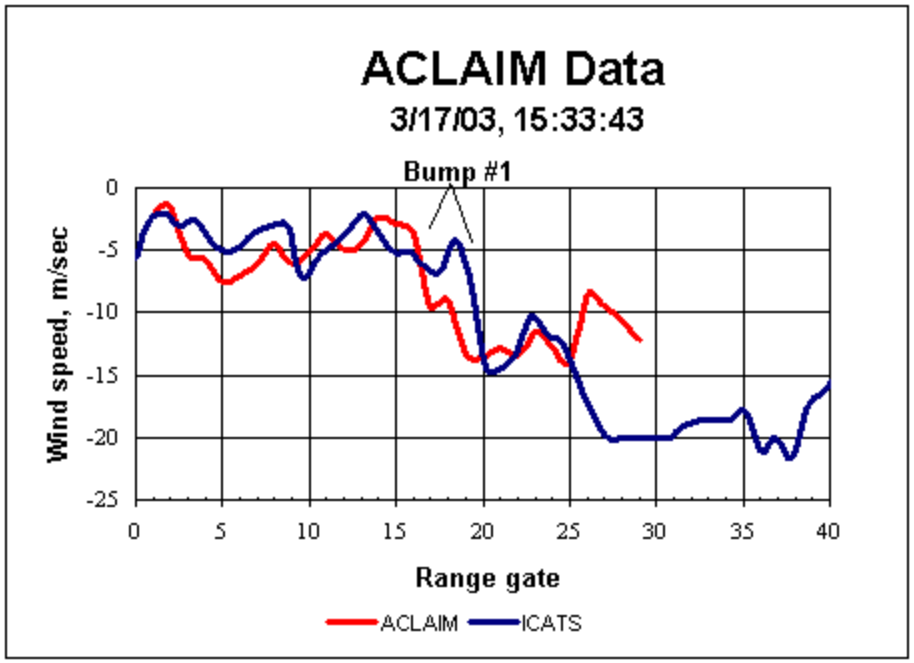


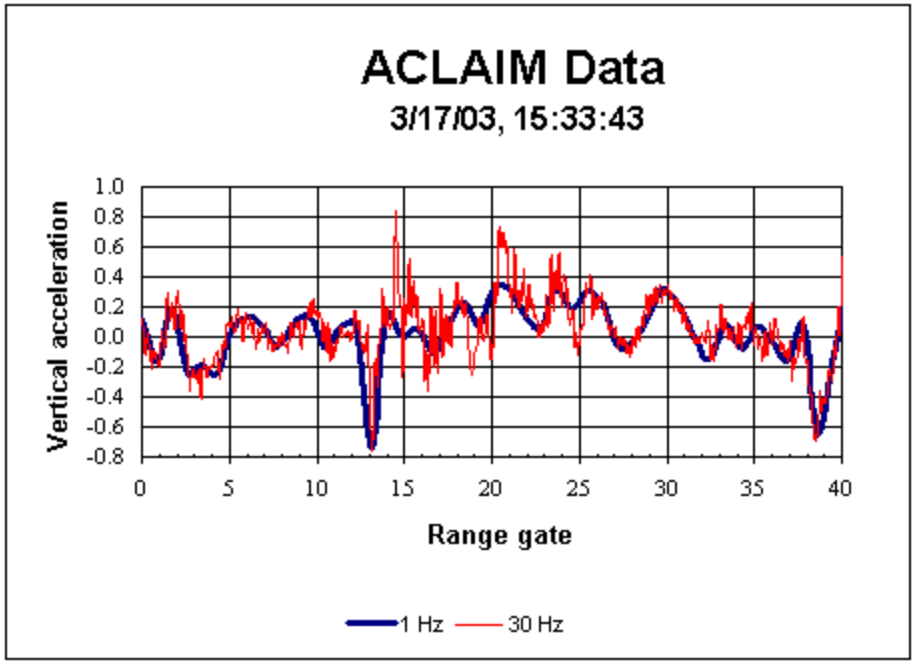

ACLAIM Data
3/17/03, 15:33:41
Bump #1
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

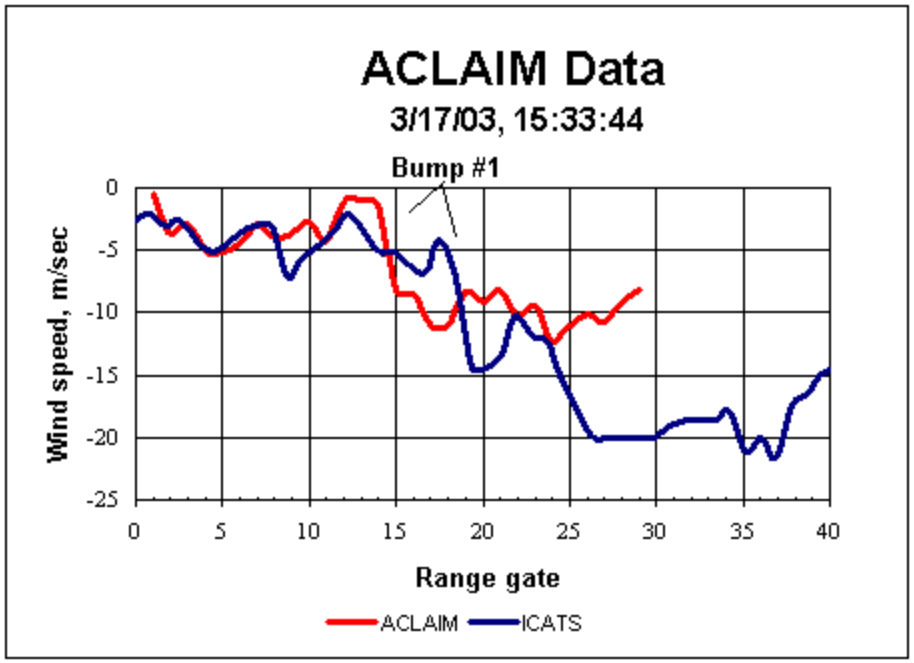

ACLAIM Data
3/17/03, 15:33:41
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

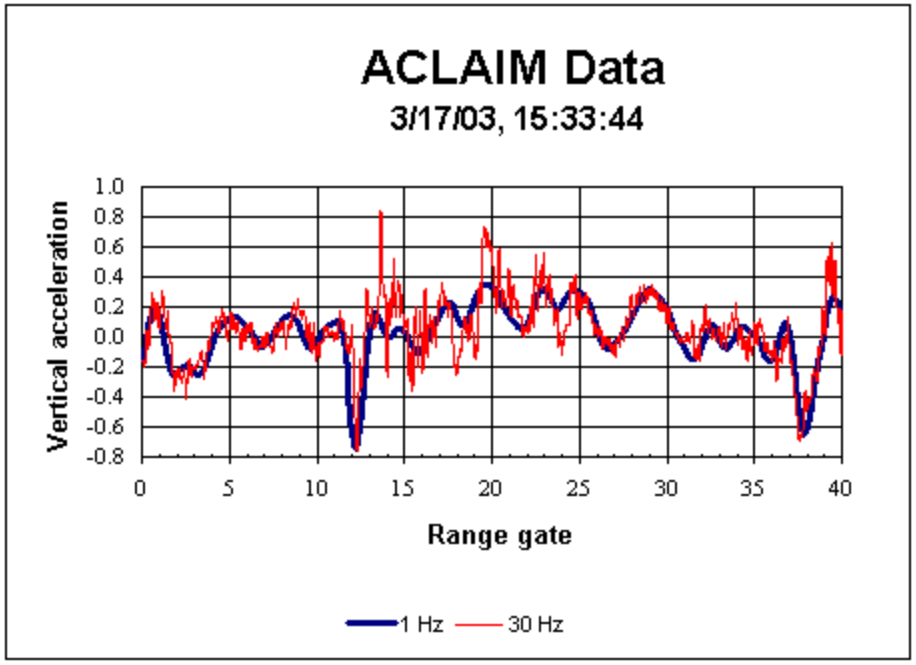

ACLAIM Data
3/17/03, 15:33:42
Bump #1
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

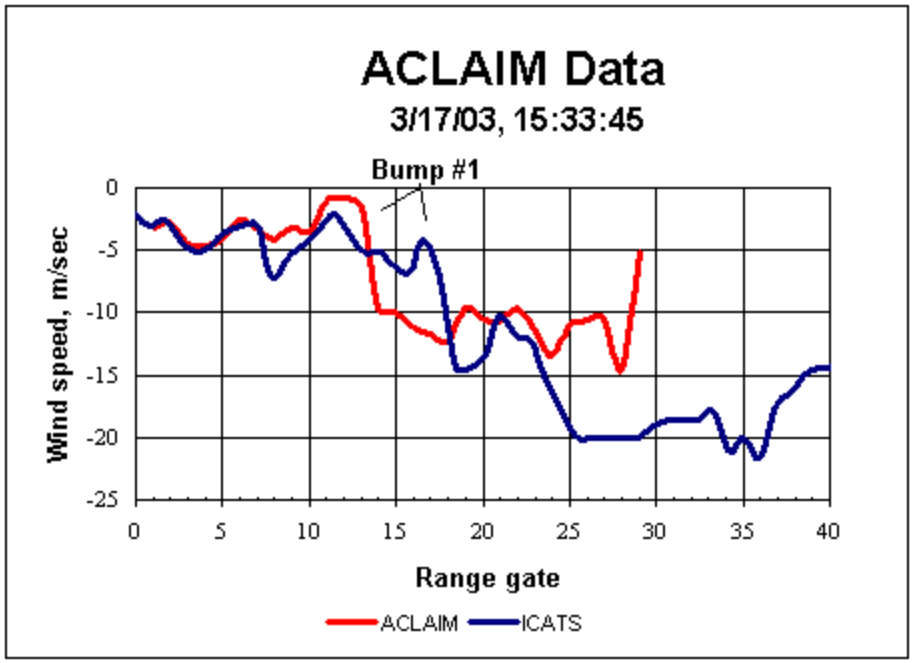

ACLAIM Data
3/17/03, 15:33:42
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

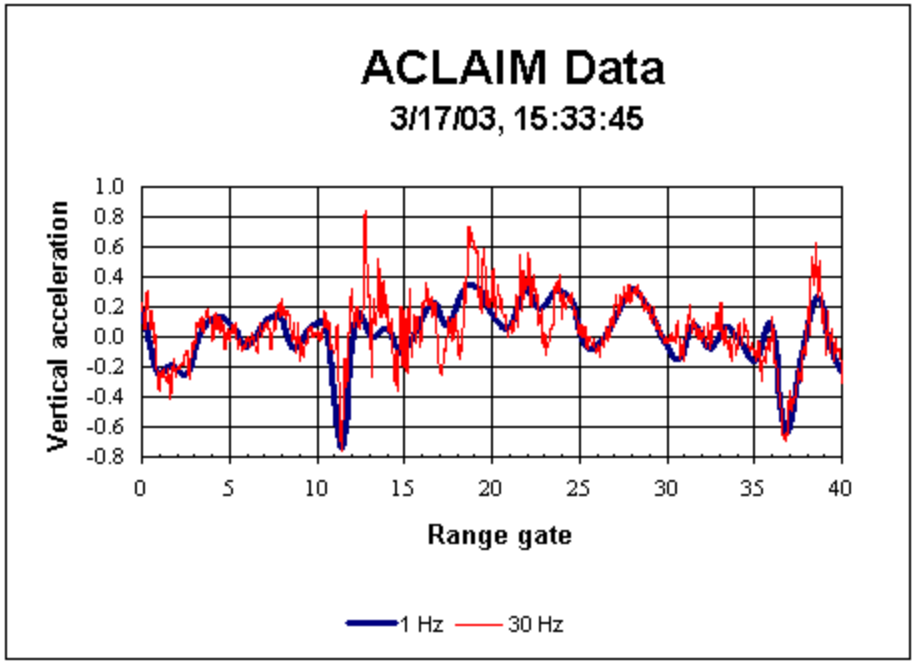

ACLAIM Data
3/17/03, 15:33:43
Bump #1
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

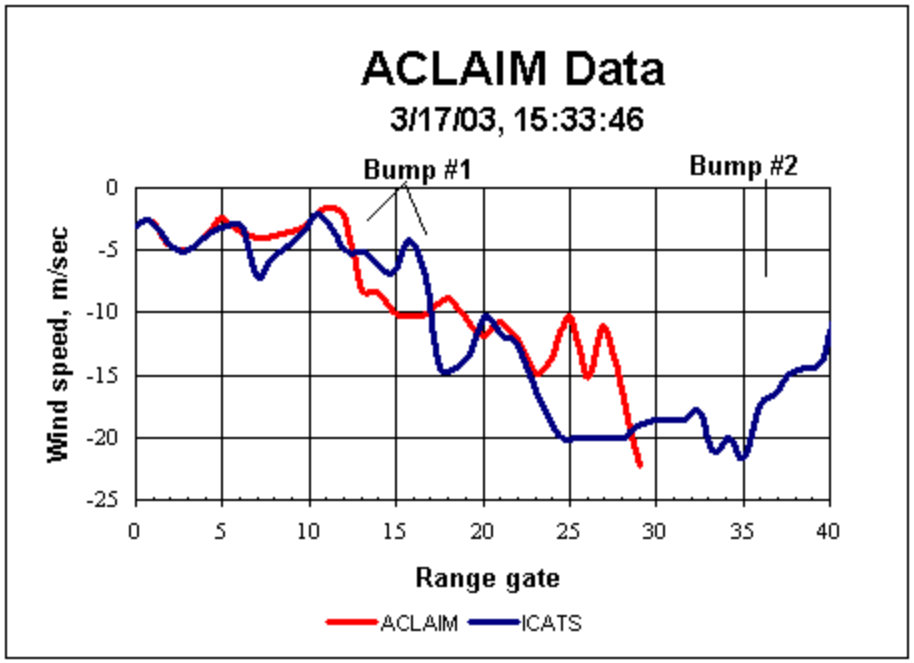

ACLAIM Data
3/17/03, 15:33:43
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

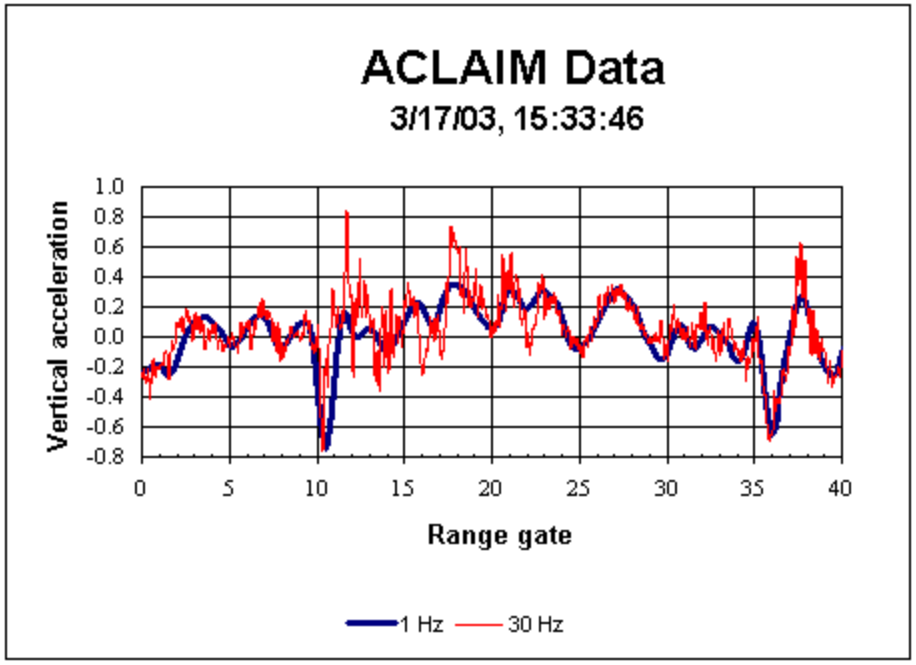

ACLAIM Data
3/17/03, 15:33:44
Bump #1
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

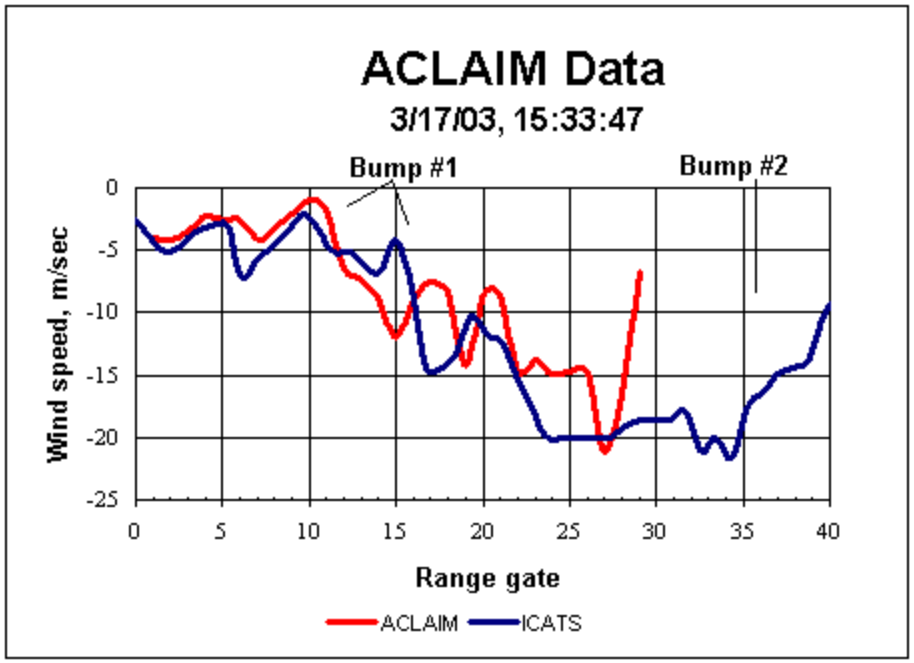

ACLAIM Data
3/17/03, 15:33:44
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

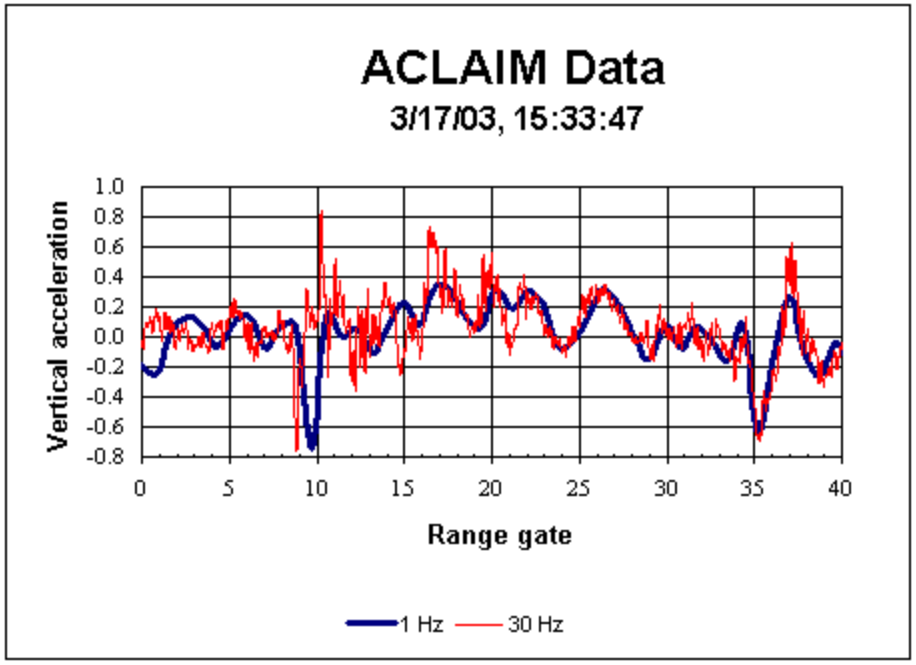

ACLAIM Data
3/17/03, 15:33:45
Bump #1
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

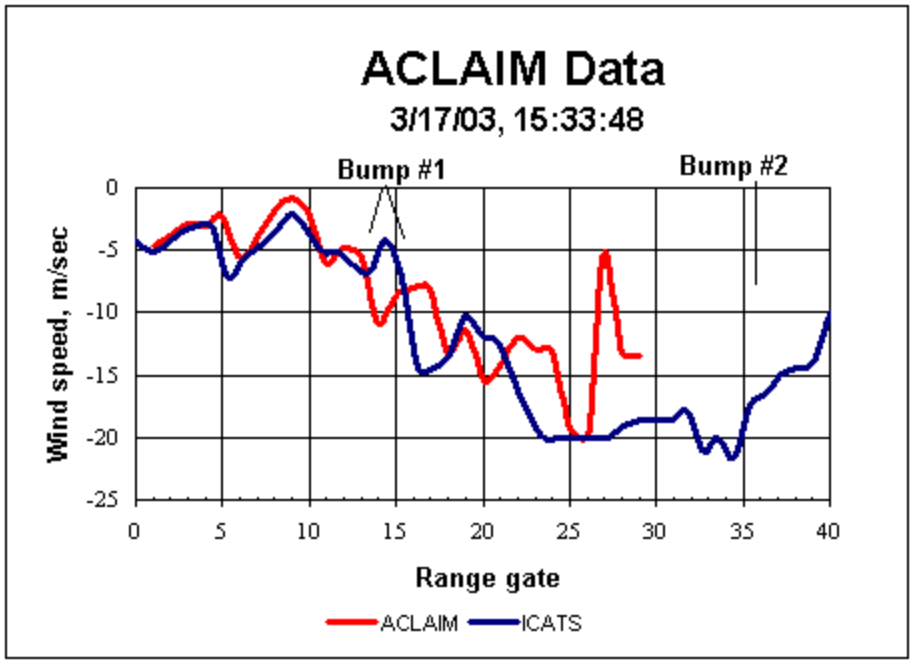

ACLAIM Data
3/17/03, 15:33:45
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

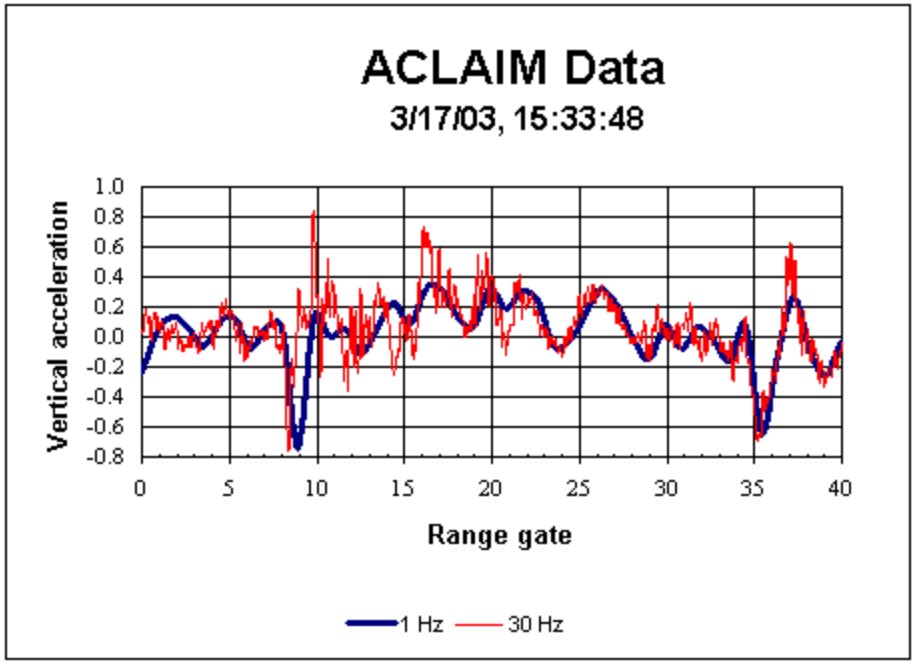

ACLAIM Data
3/17/03, 15:33:46
Bump #1
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

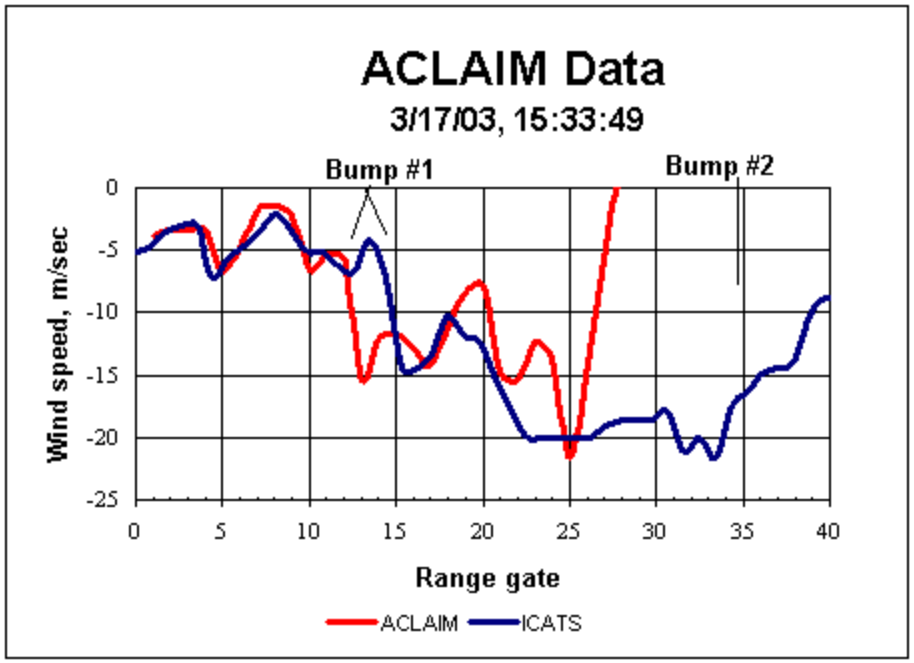

ACLAIM Data
3/17/03, 15:33:46
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

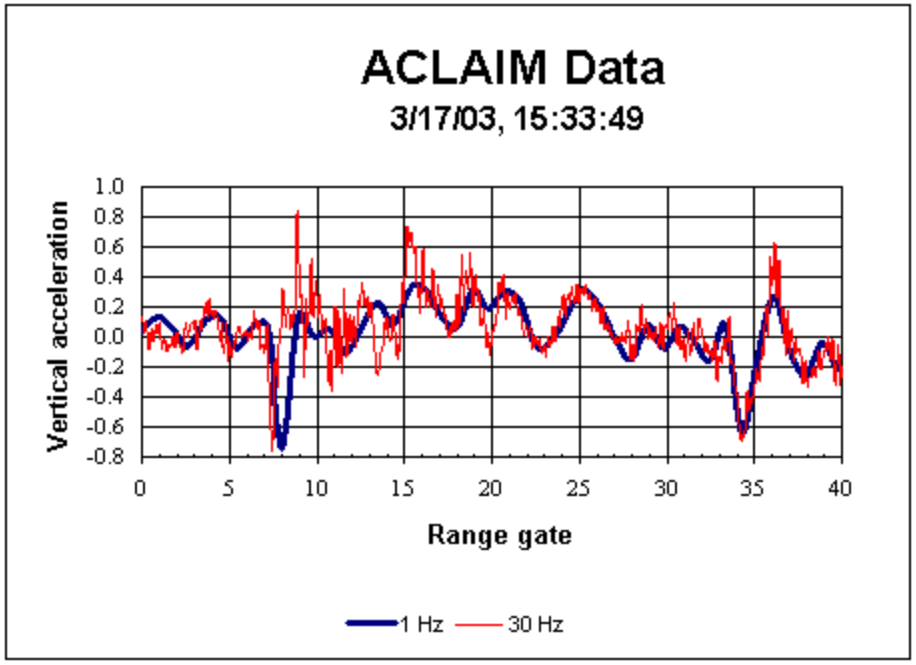

ACLAIM Data
3/17/03, 15:33:47
Bump #1
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

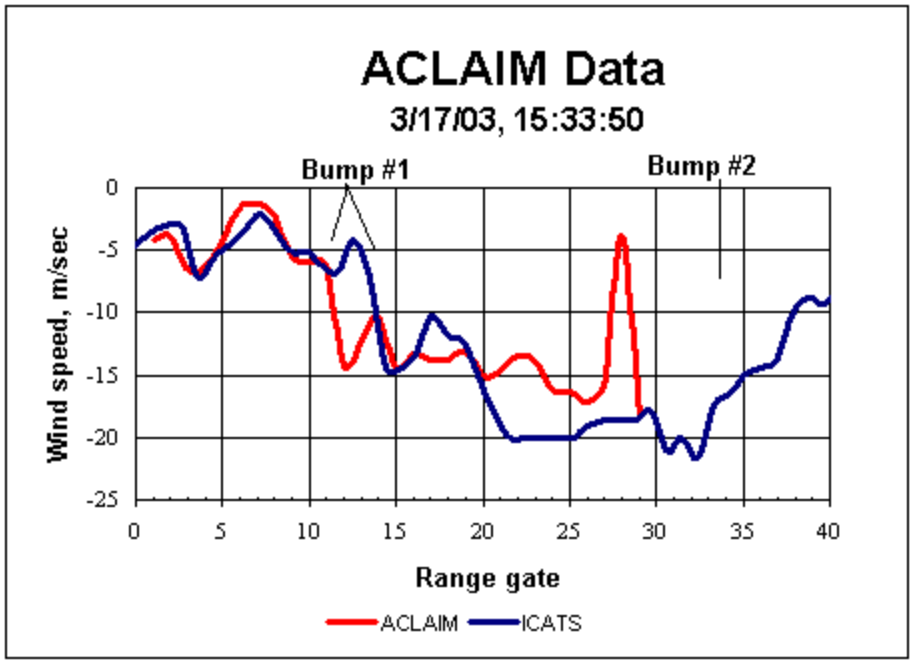

ACLAIM Data
3/17/03, 15:33:47
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

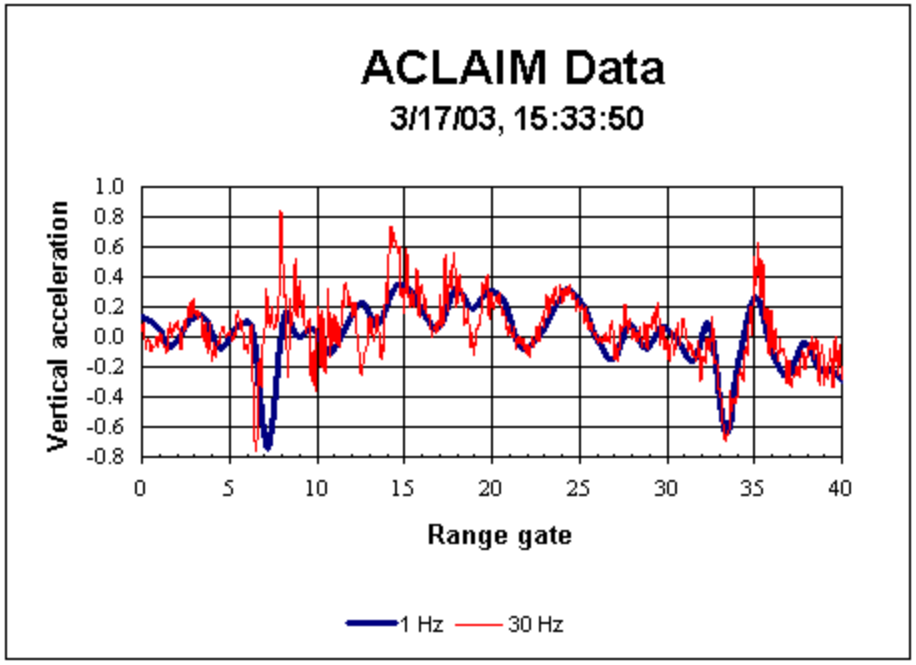

ACLAIM Data
3/17/03, 15:33:48
Bump #1
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

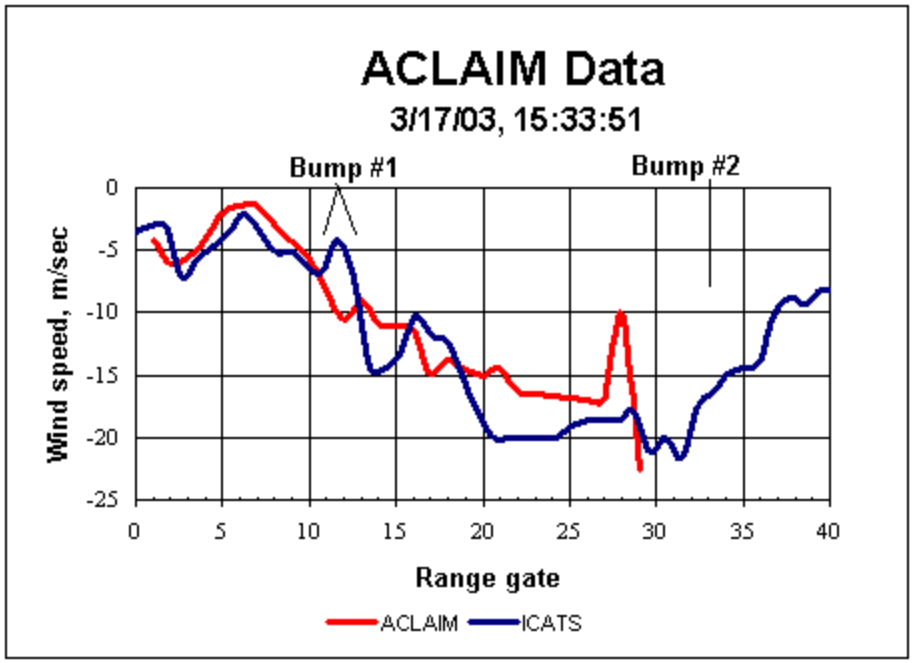

ACLAIM Data
3/17/03, 15:33:48
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

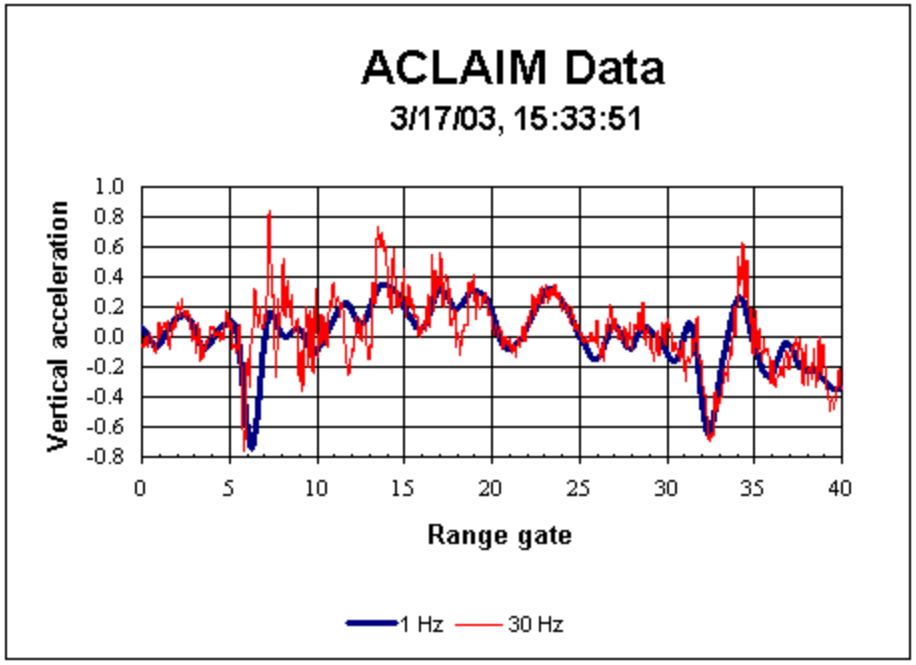

ACLAIM Data
3/17/03, 15:33:49
Bump #1
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

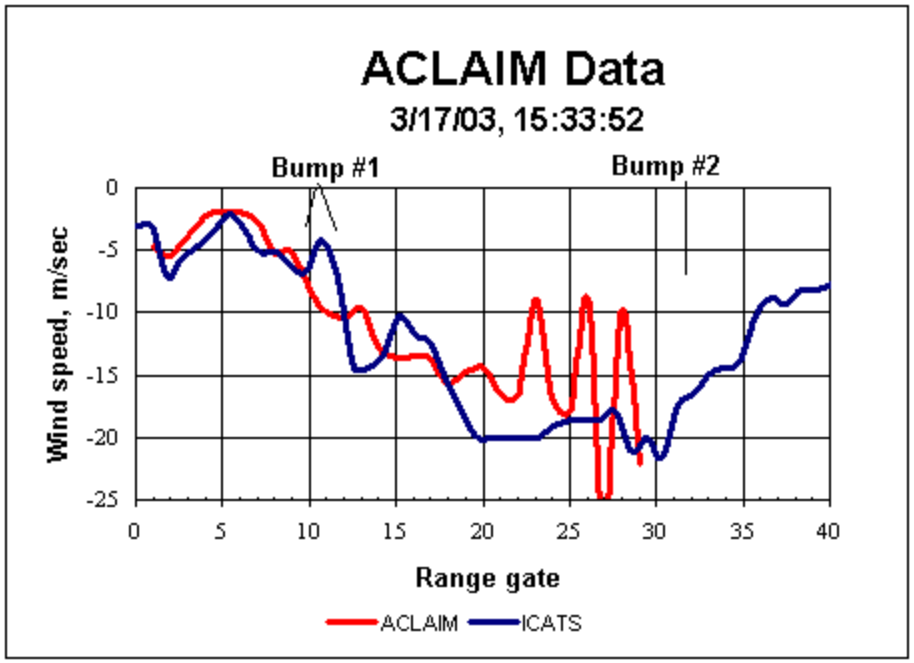

ACLAIM Data
3/17/03, 15:33:49
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

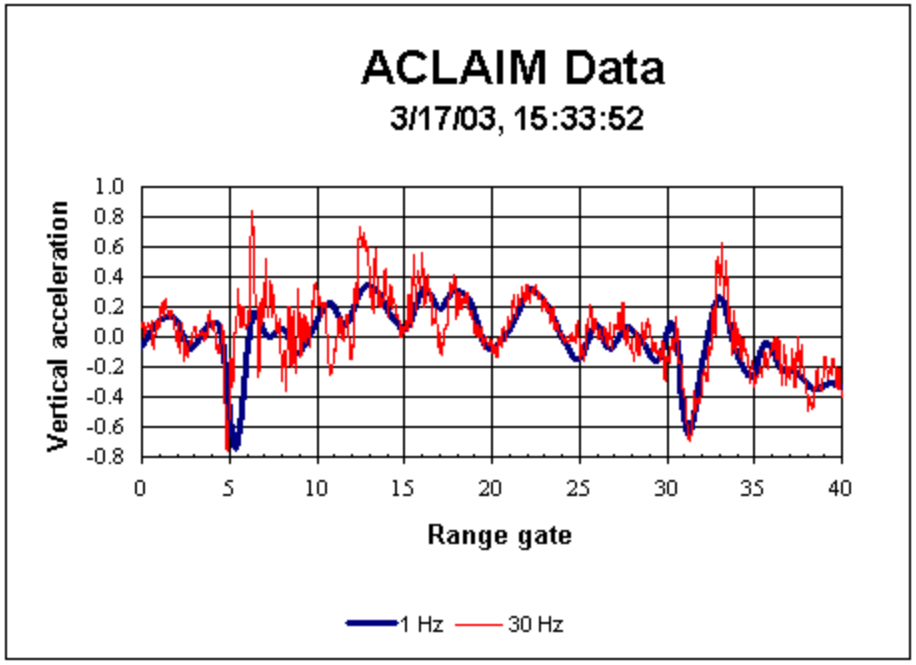

ACLAIM Data
3/17/03, 15:33:50
Bump #1
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

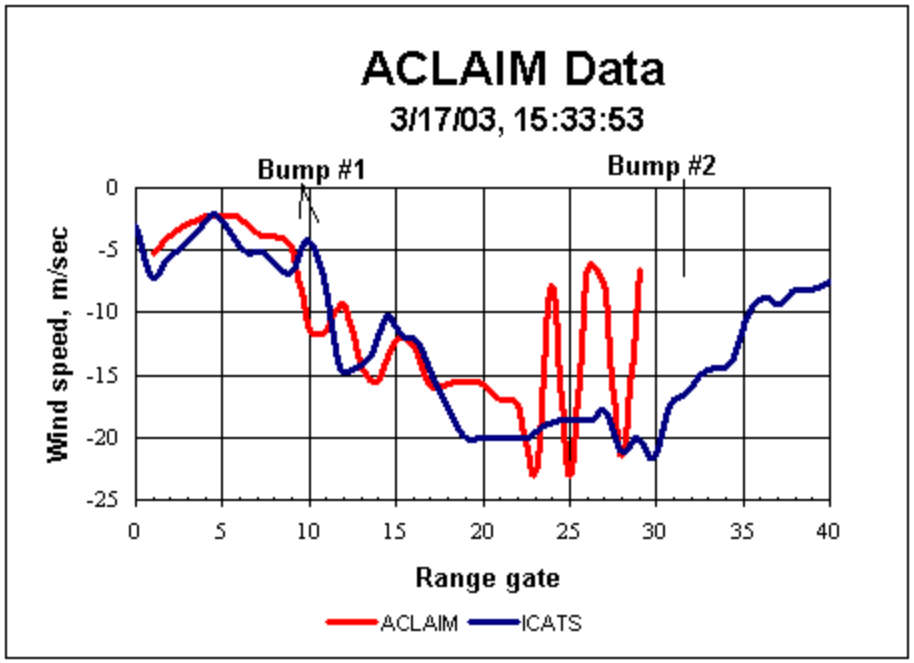

ACLAIM Data
3/17/03, 15:33:50
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

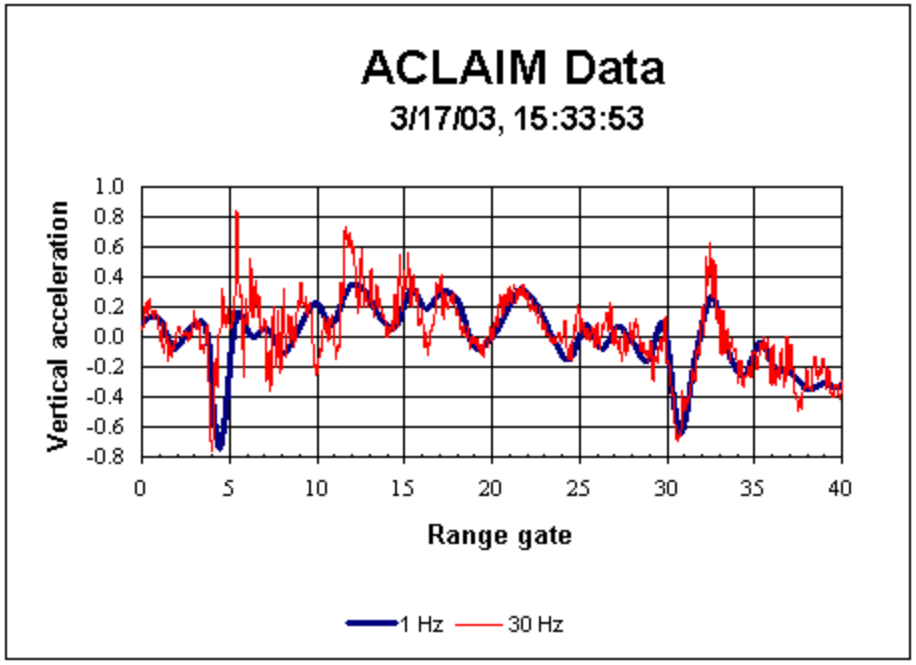

ACLAIM Data
3/17/03, 15:33:51
Bump #1
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

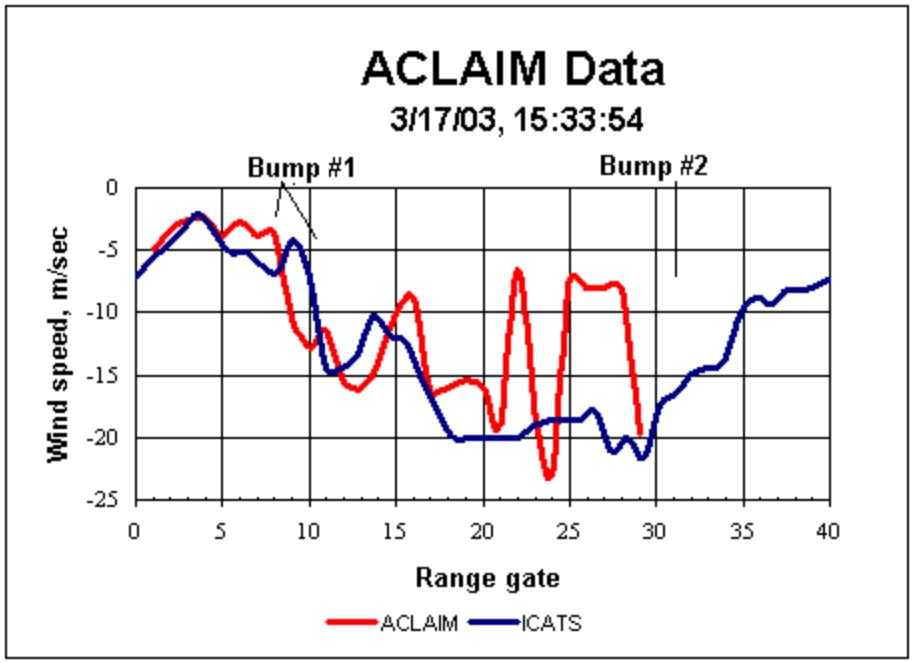

ACLAIM Data
3/17/03, 15:33:51
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

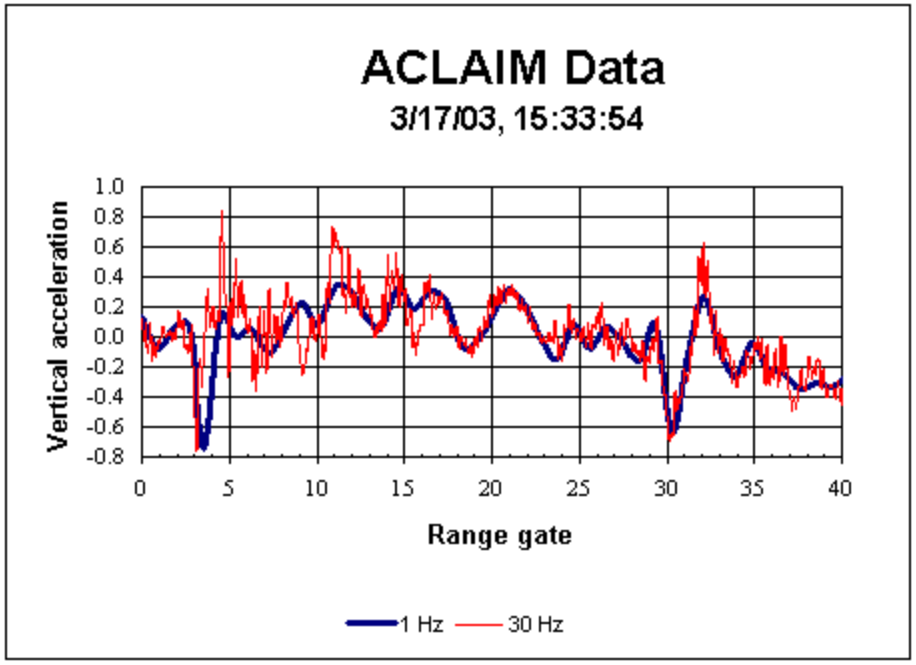

ACLAIM Data
3/17/03, 15:33:52
Bump #1
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

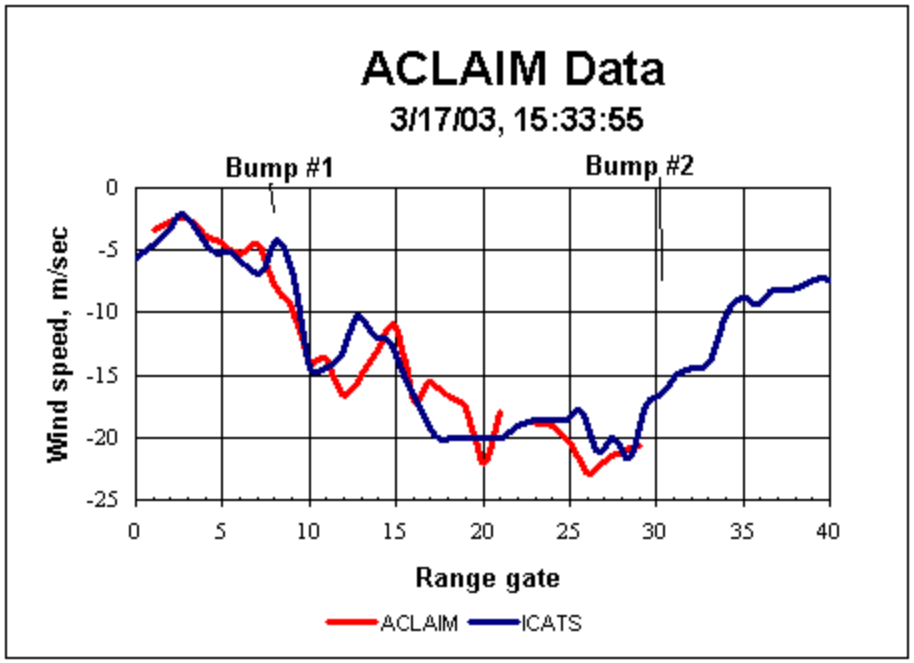

ACLAIM Data
3/17/03, 15:33:52
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

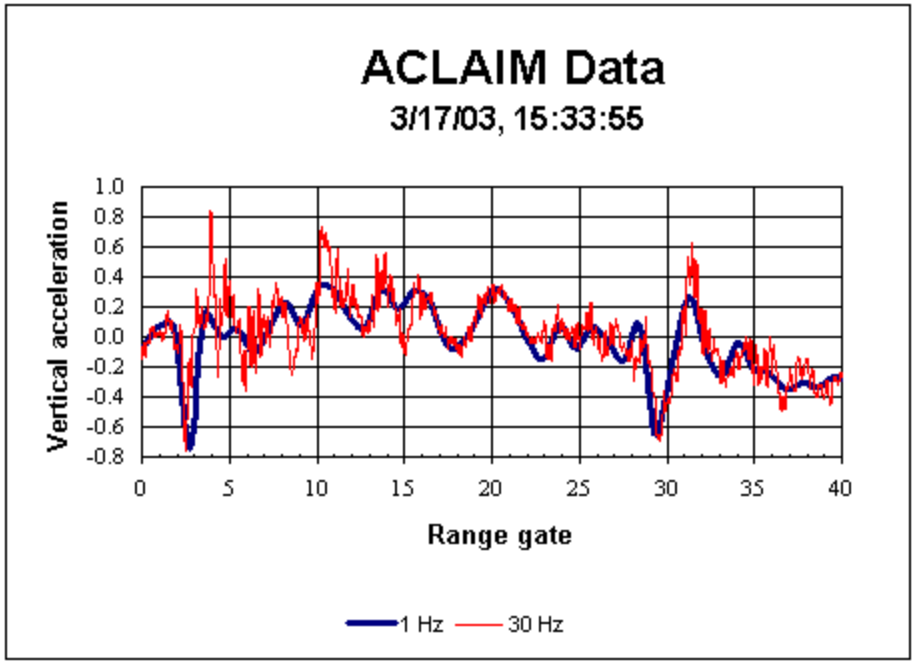

ACLAIM Data
3/17/03, 15:33:53
Bump #1
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

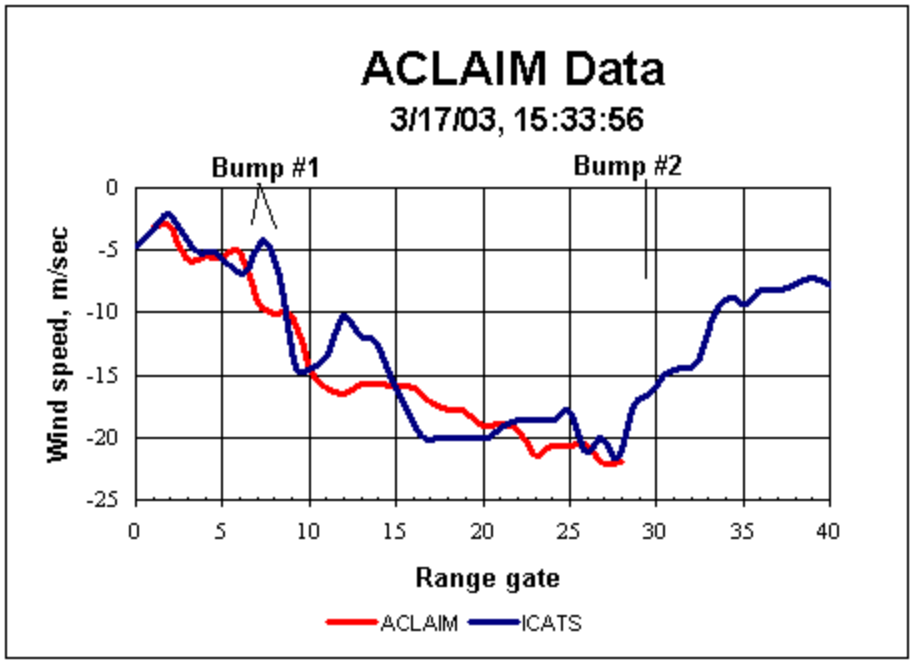

ACLAIM Data
3/17/03, 15:33:53
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

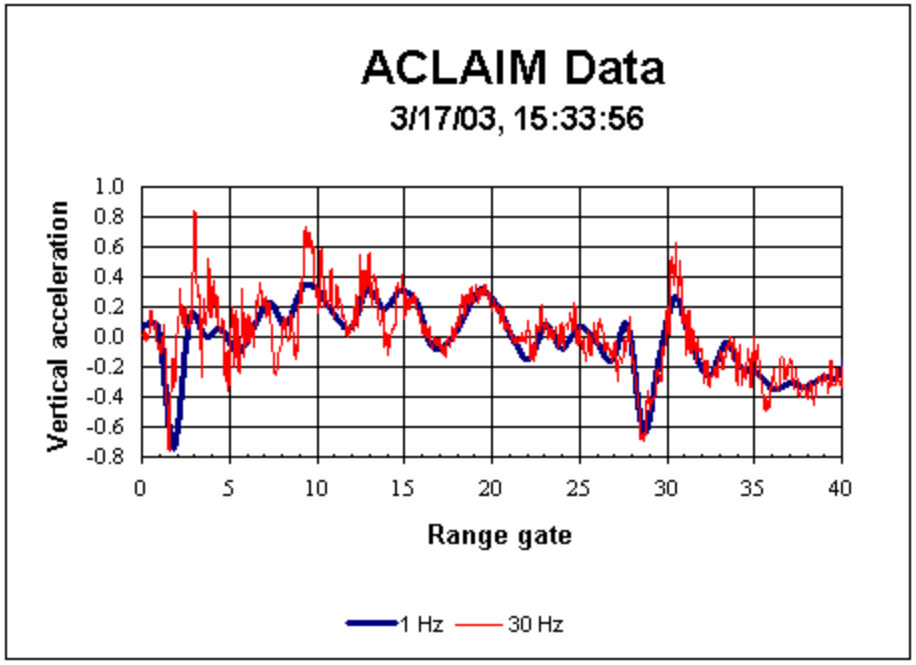

ACLAIM Data
3/17/03, 15:33:54
Bump #1
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

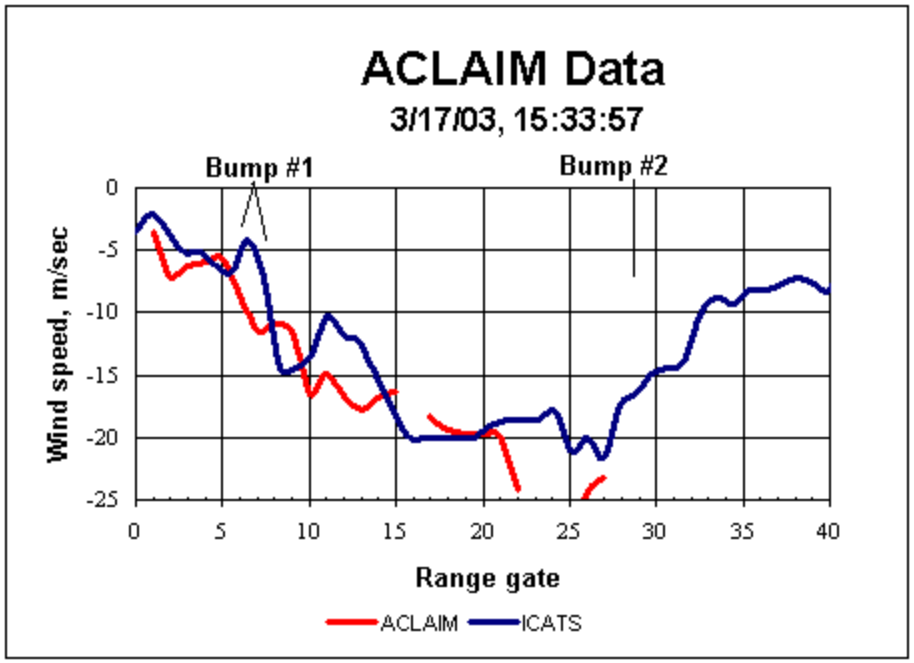

ACLAIM Data
3/17/03, 15:33:54
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

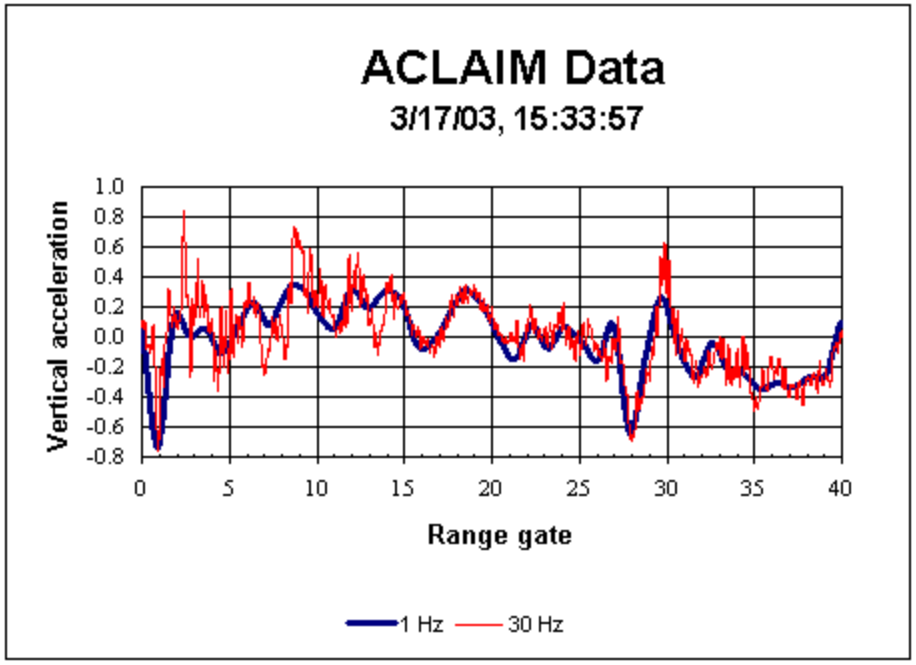

ACLAIM Data
3/17/03, 15:33:55
Bump #1
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

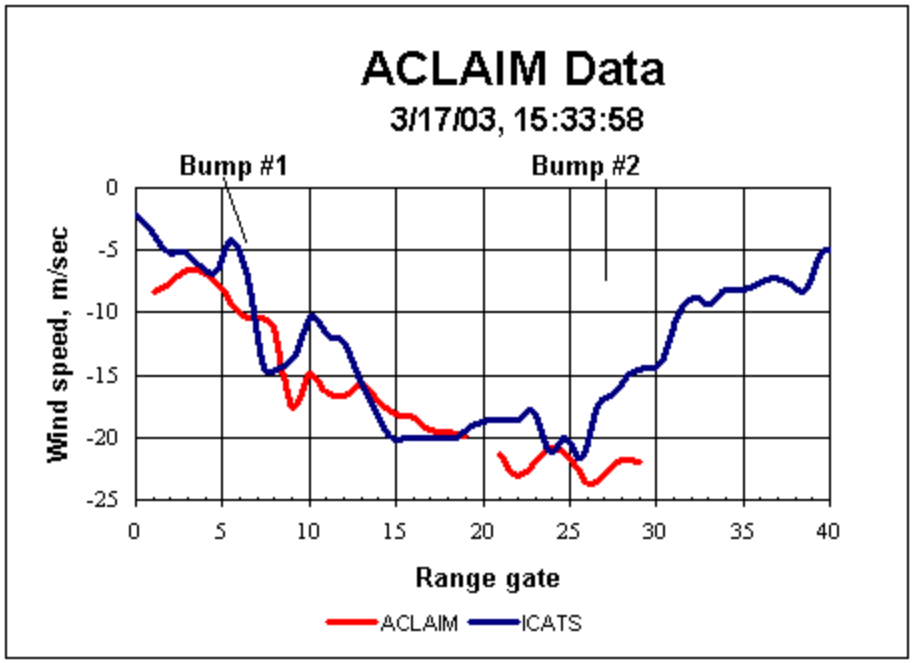

ACLAIM Data
3/17/03, 15:33:55
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

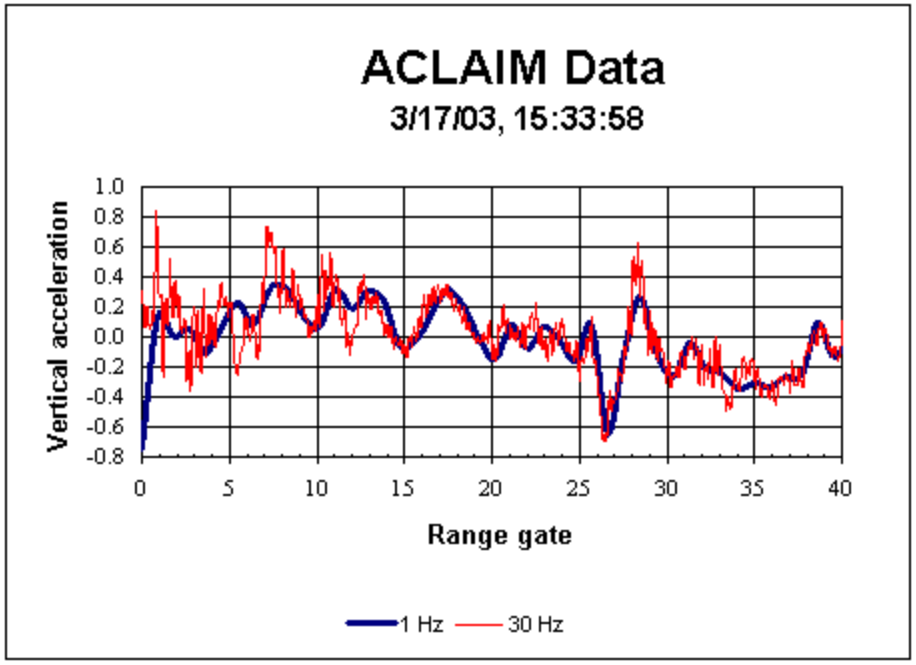

ACLAIM Data
3/17/03, 15:33:56
Bump #1
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

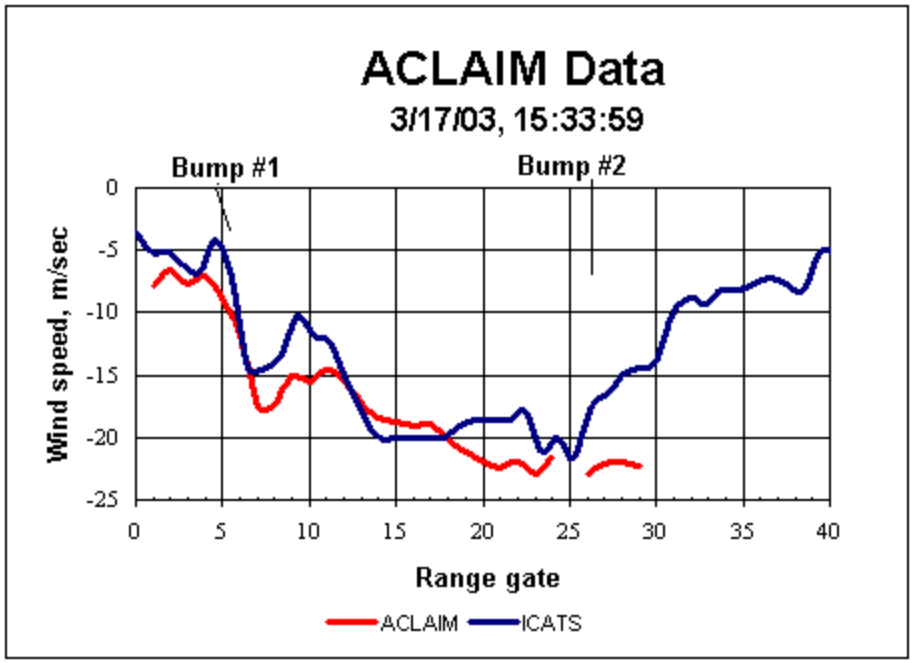

ACLAIM Data
3/17/03, 15:33:56
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

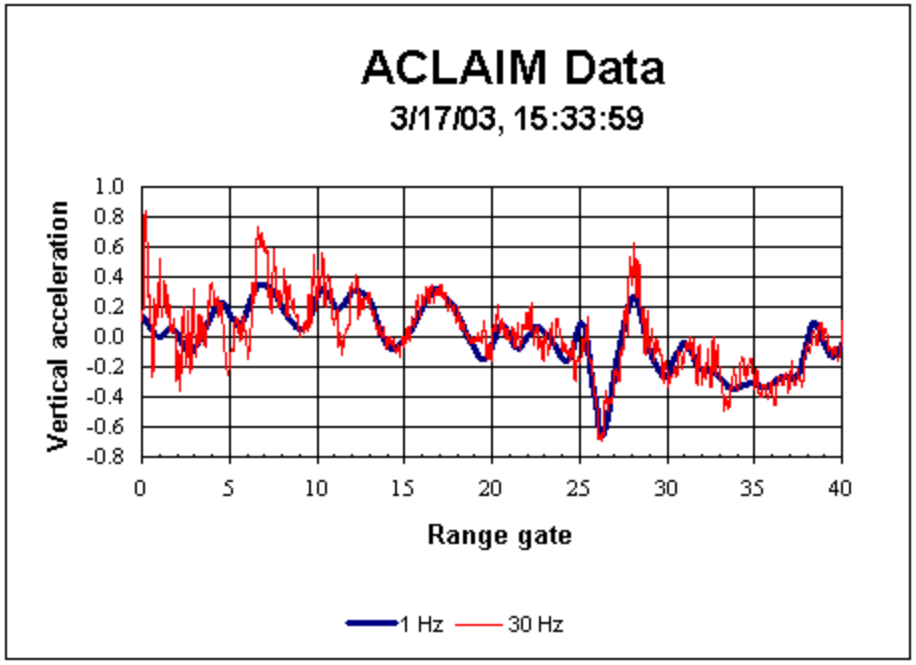

ACLAIM Data
3/17/03, 15:33:57
Bump #1
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

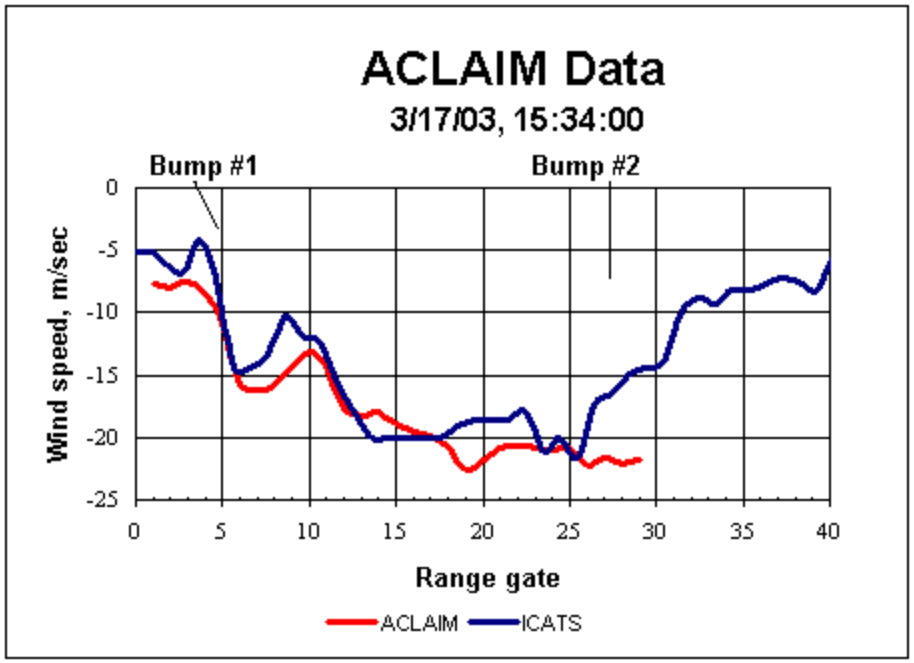

ACLAIM Data
3/17/03, 15:33:57
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

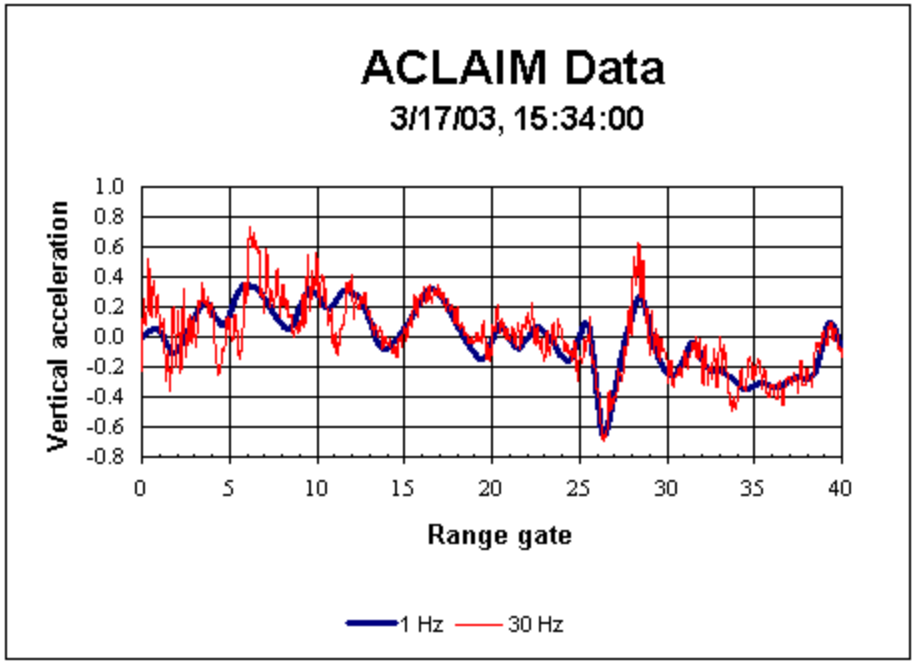

ACLAIM Data
3/17/03, 15:33:58
Bump #1
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

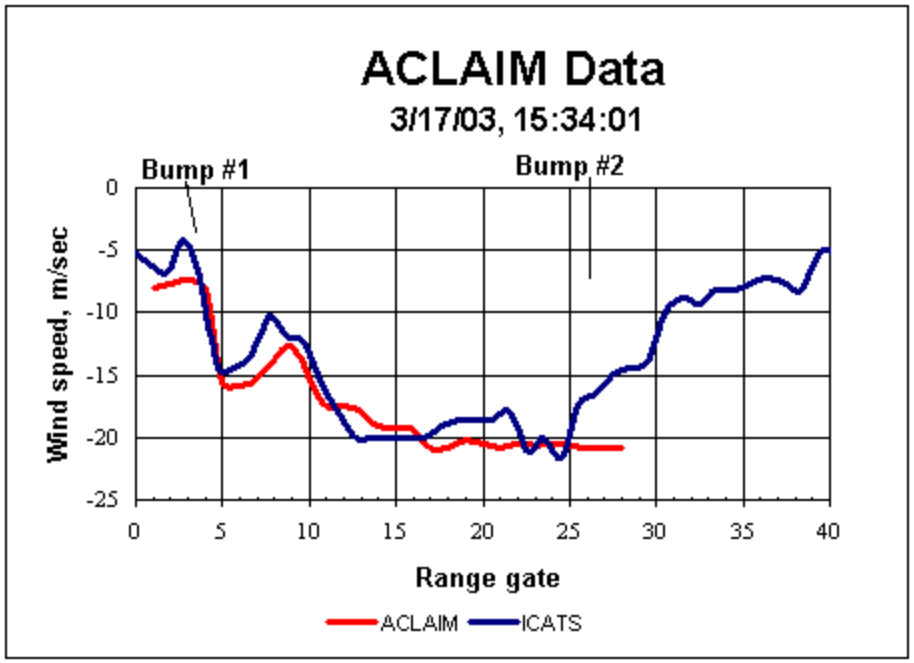

ACLAIM Data
3/17/03, 15:33:58
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

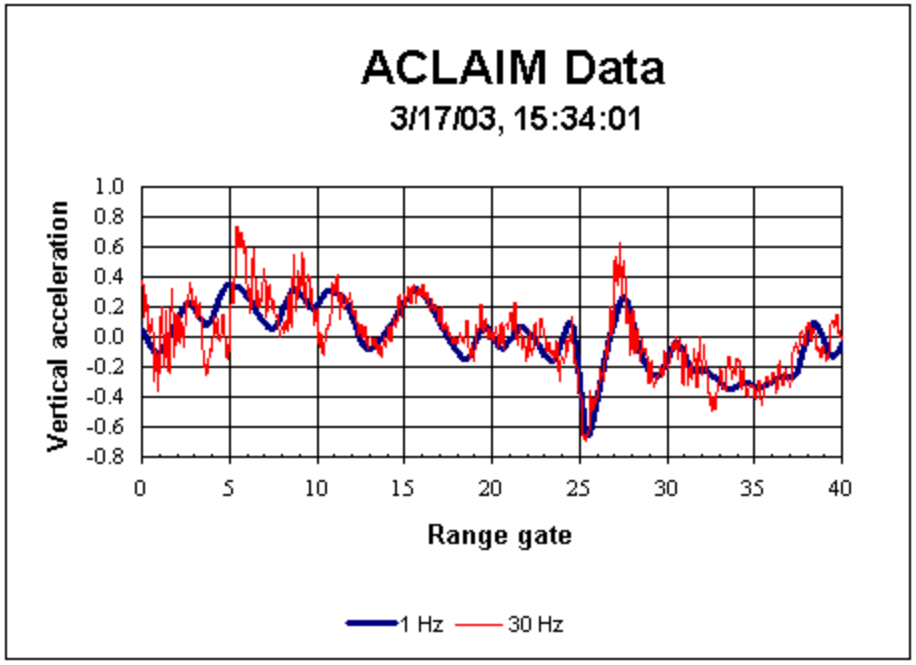

ACLAIM Data
3/17/03, 15:33:59
Bump #1
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

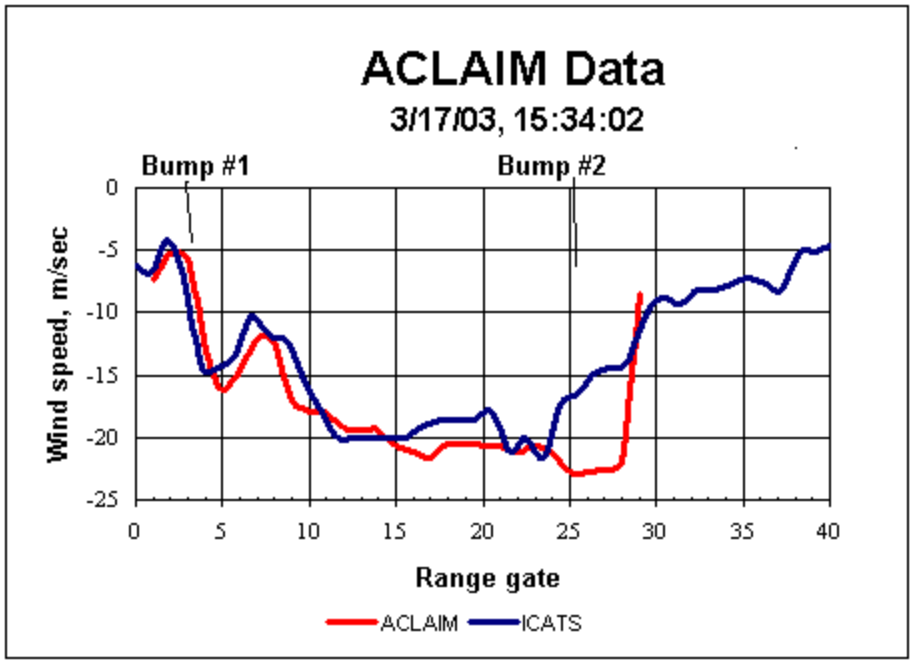

ACLAIM Data
3/17/03, 15:33:59
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

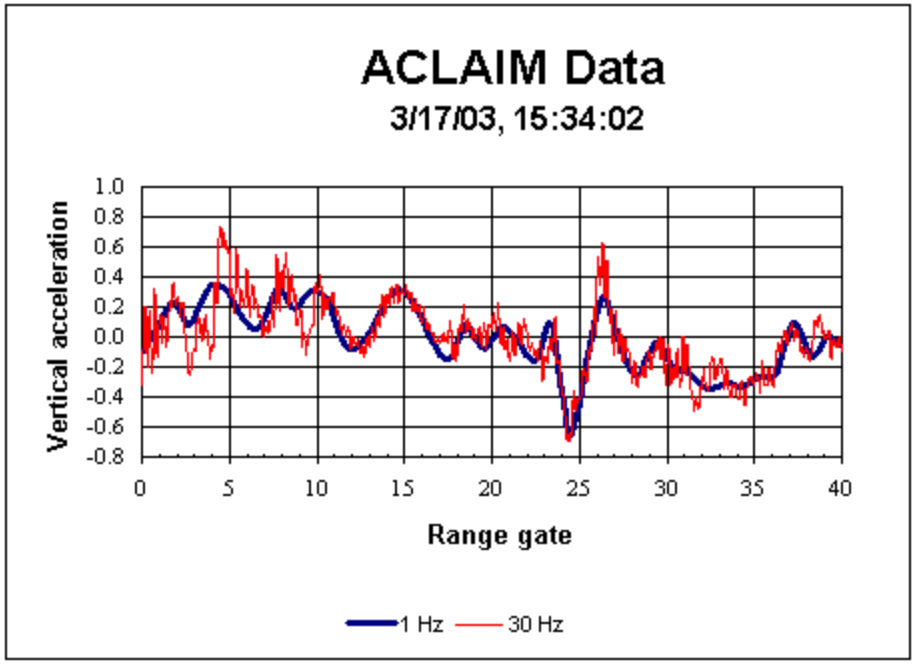

ACLAIM Data
3/17/03, 15:34:00
Bump #1
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

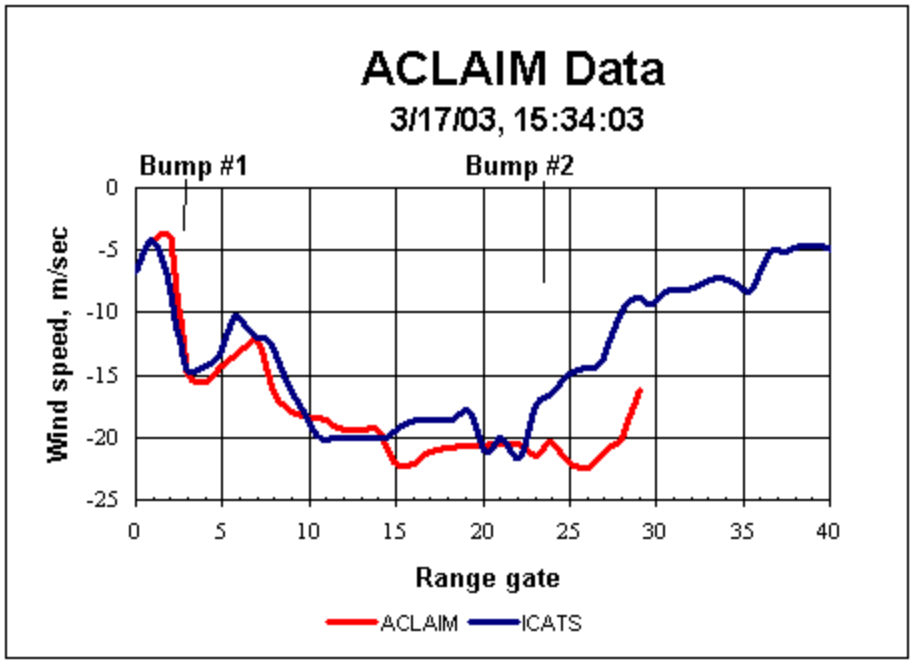

ACLAIM Data
3/17/03, 15:34:00
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

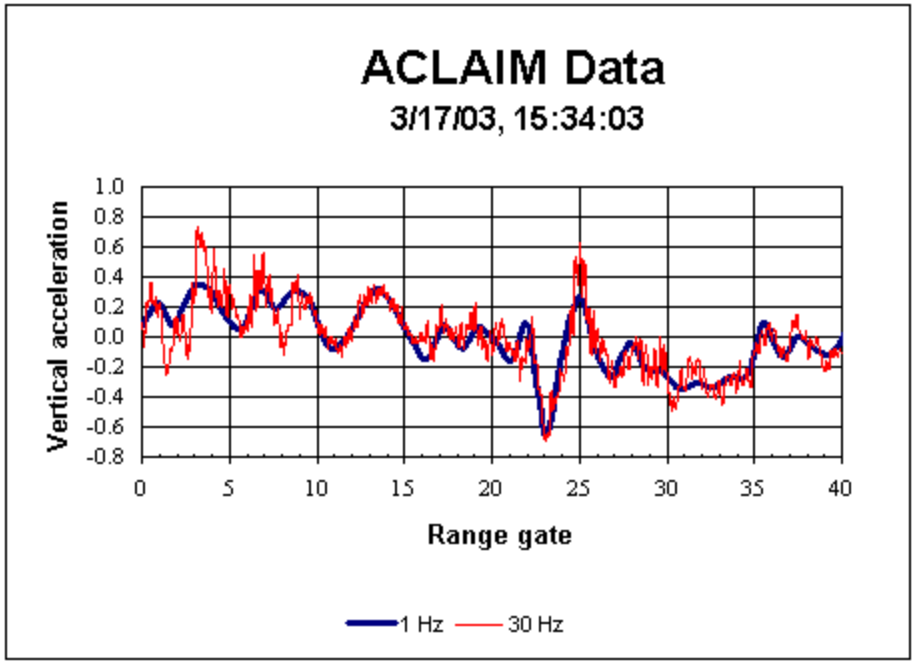

ACLAIM Data
3/17/03, 15:34:01
Bump #1
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

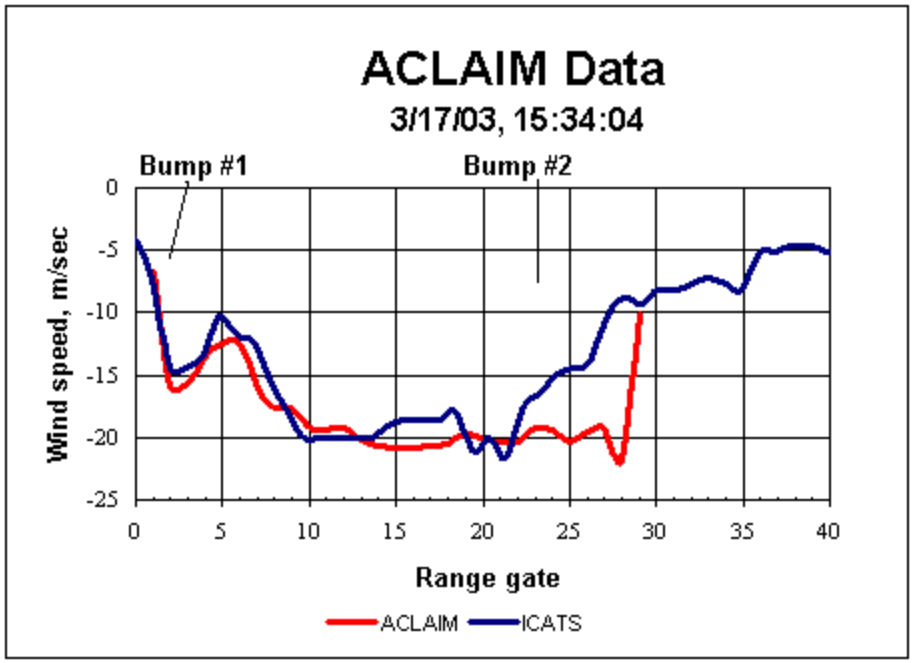

ACLAIM Data
3/17/03, 15:34:01
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

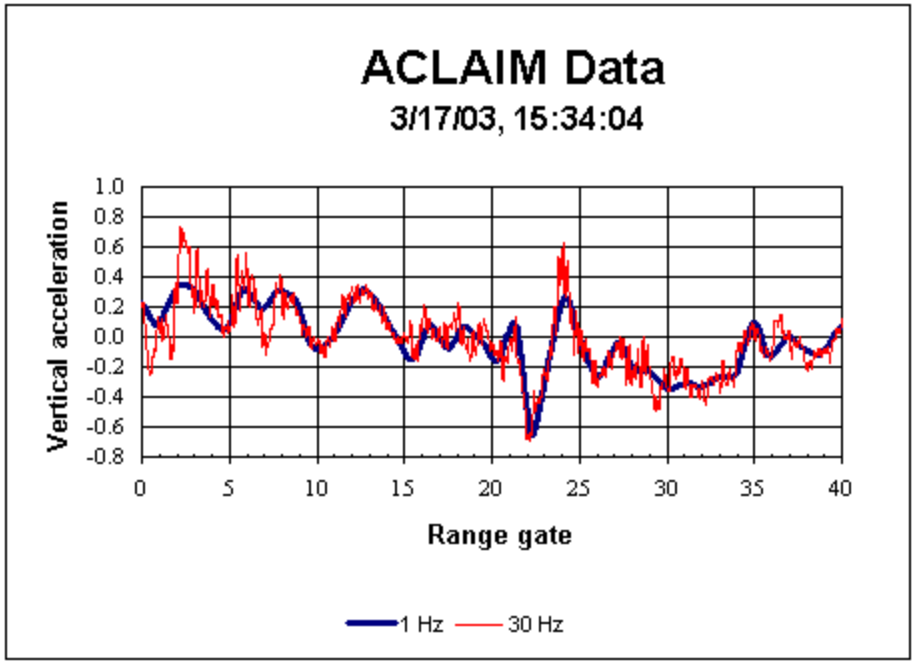

ACLAIM Data
3/17/03, 15:34:02
Bump #1
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

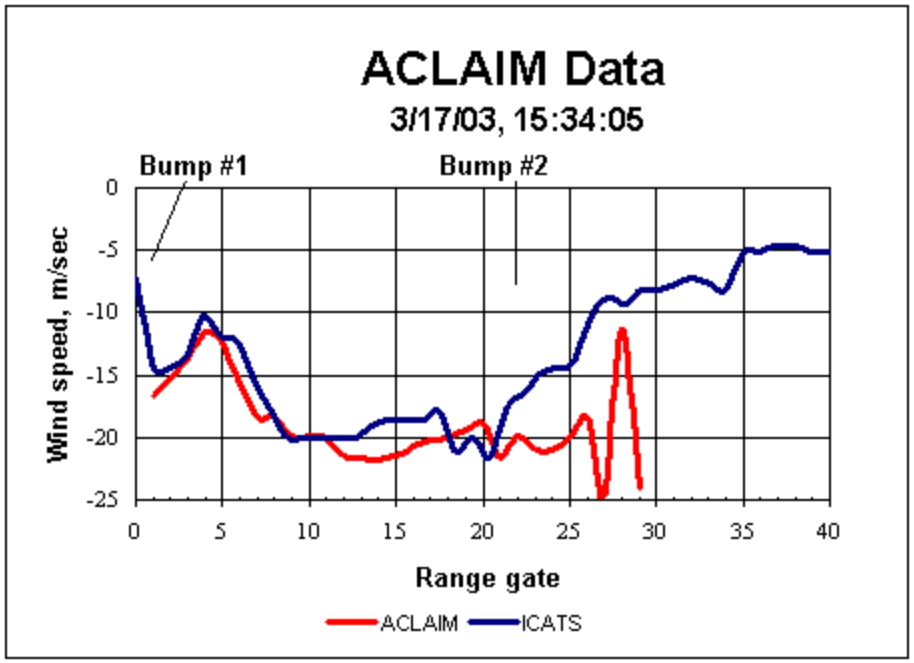

ACLAIM Data
3/17/03, 15:34:02
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

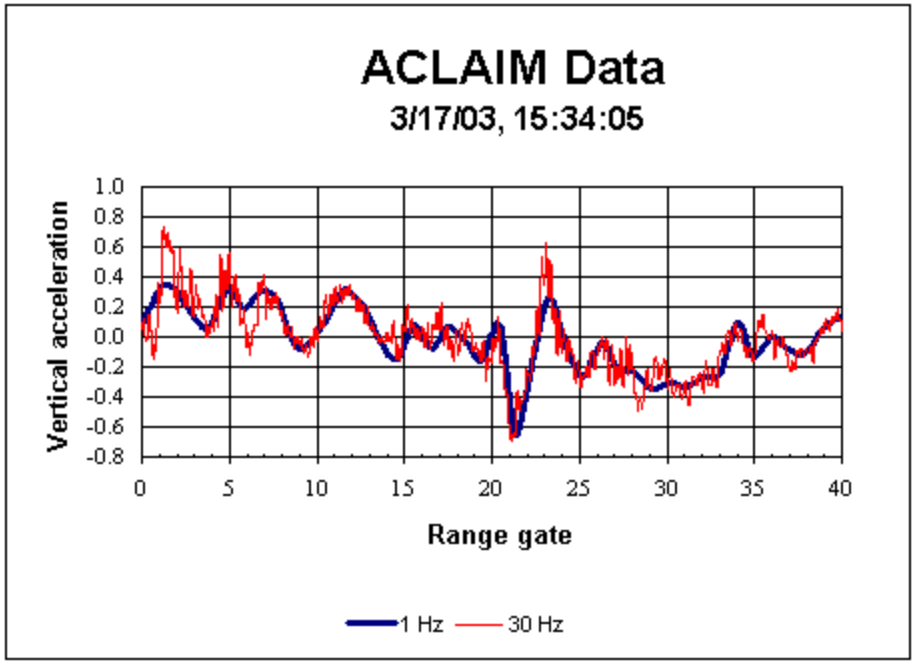

ACLAIM Data
3/17/03, 15:34:03
Bump #1
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

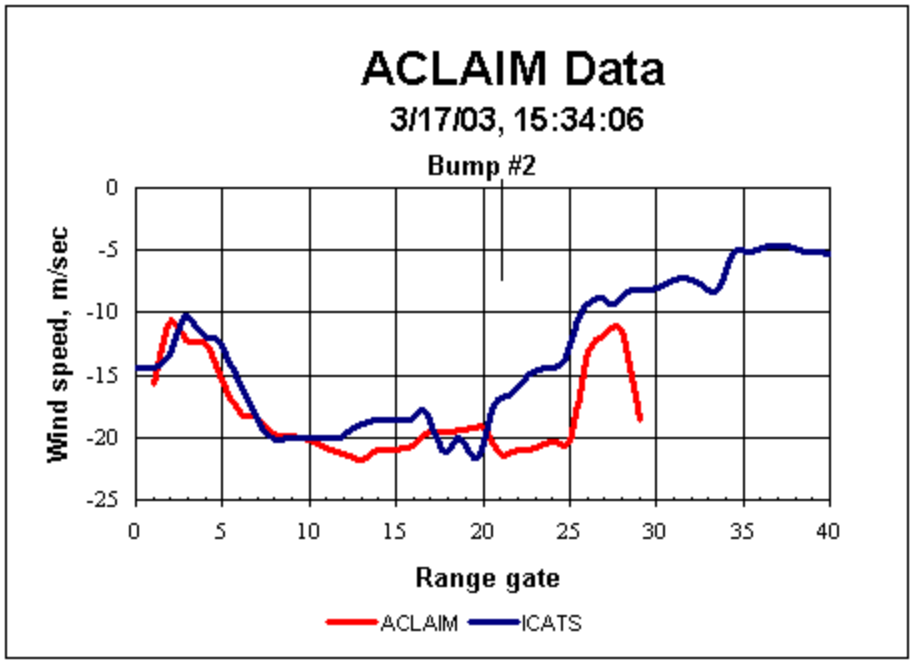

ACLAIM Data
3/17/03, 15:34:03
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

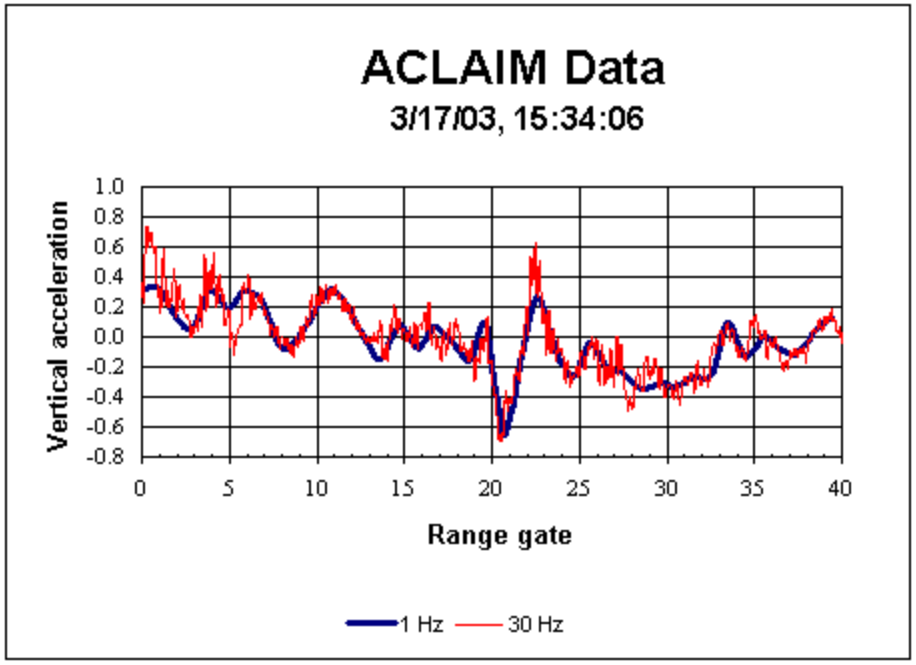

ACLAIM Data
3/17/03, 15:34:04
Bump #1
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

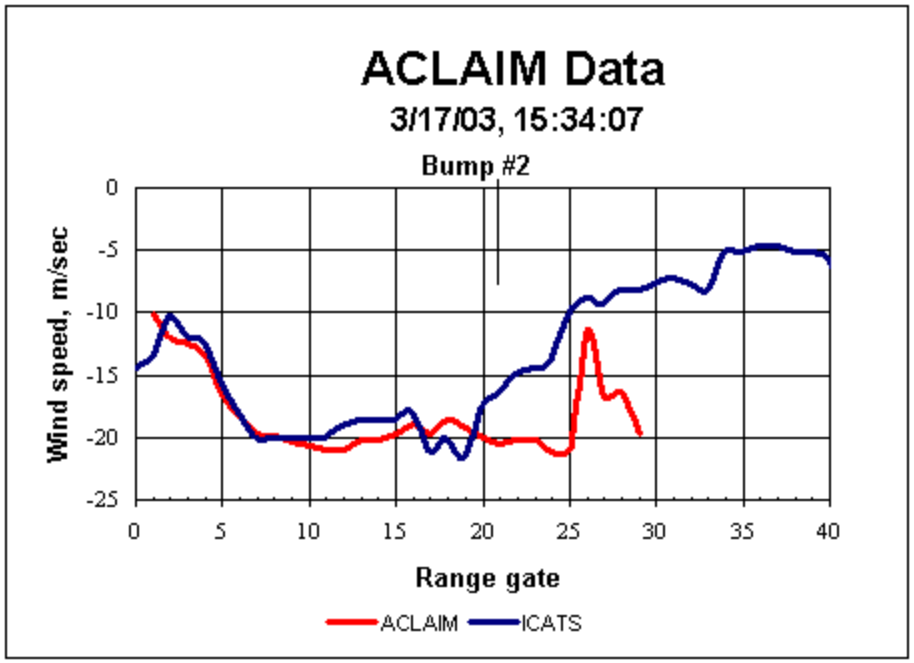

ACLAIM Data
3/17/03, 15:34:04
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

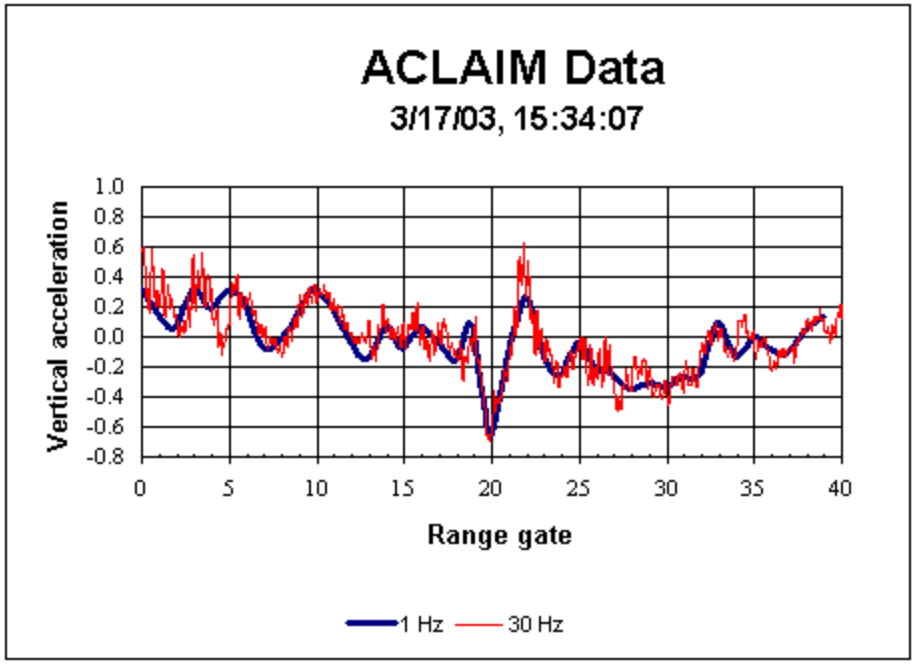

ACLAIM Data
3/17/03, 15:34:05
Bump #1
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

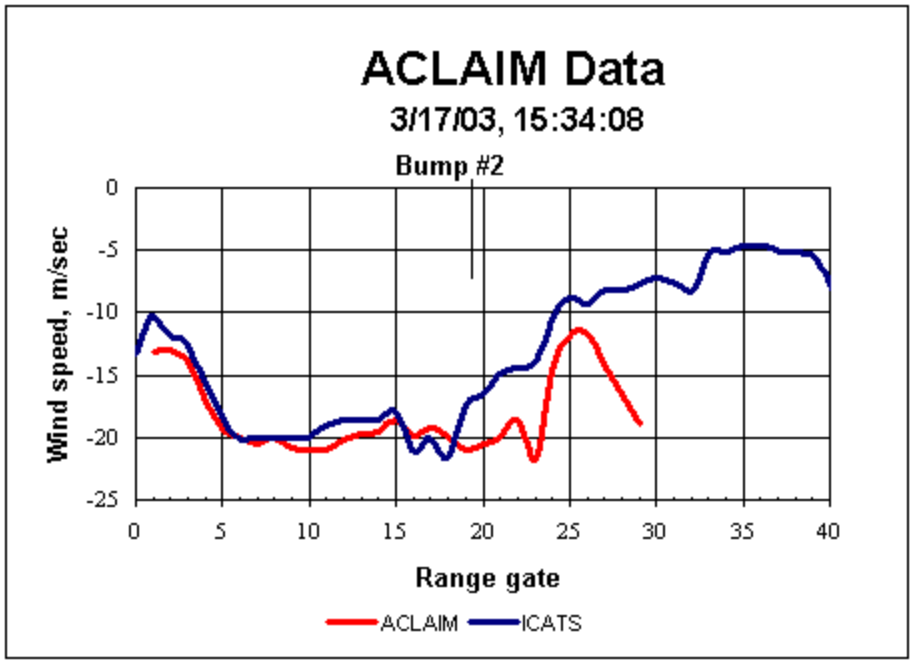

ACLAIM Data
3/17/03, 15:34:05
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

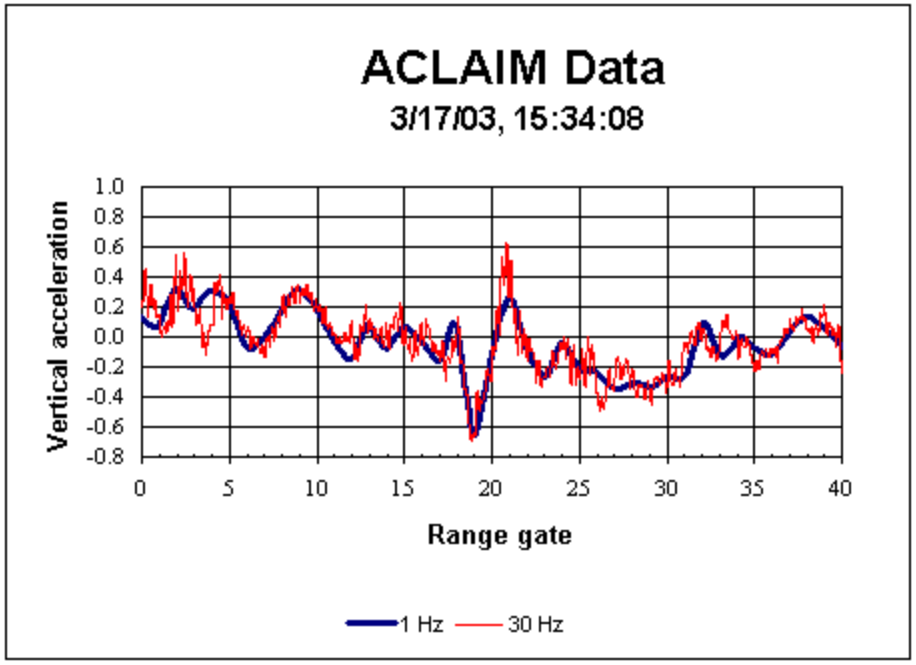

ACLAIM Data
3/17/03, 15:34:06
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

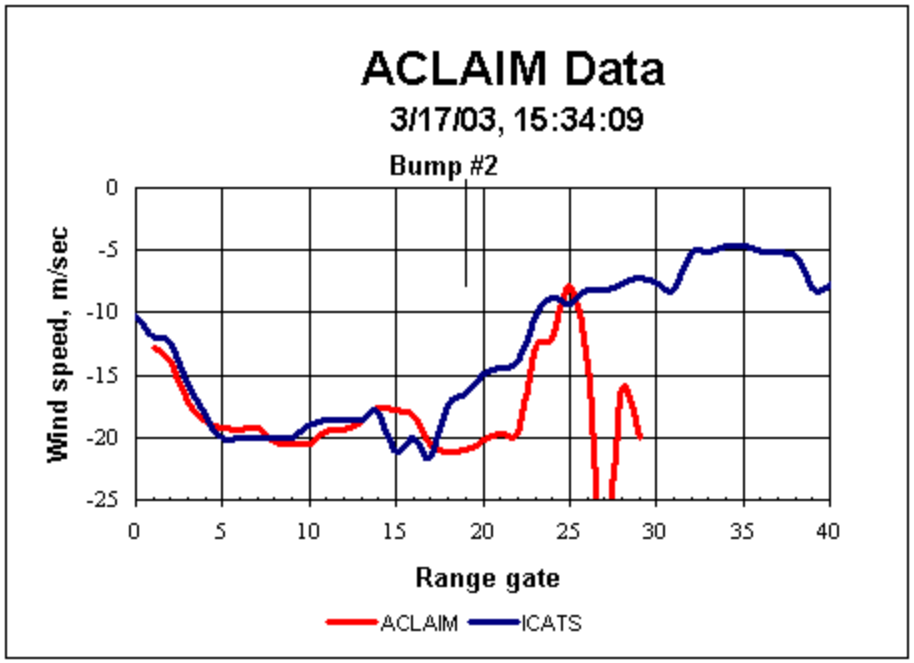

ACLAIM Data
3/17/03, 15:34:06
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

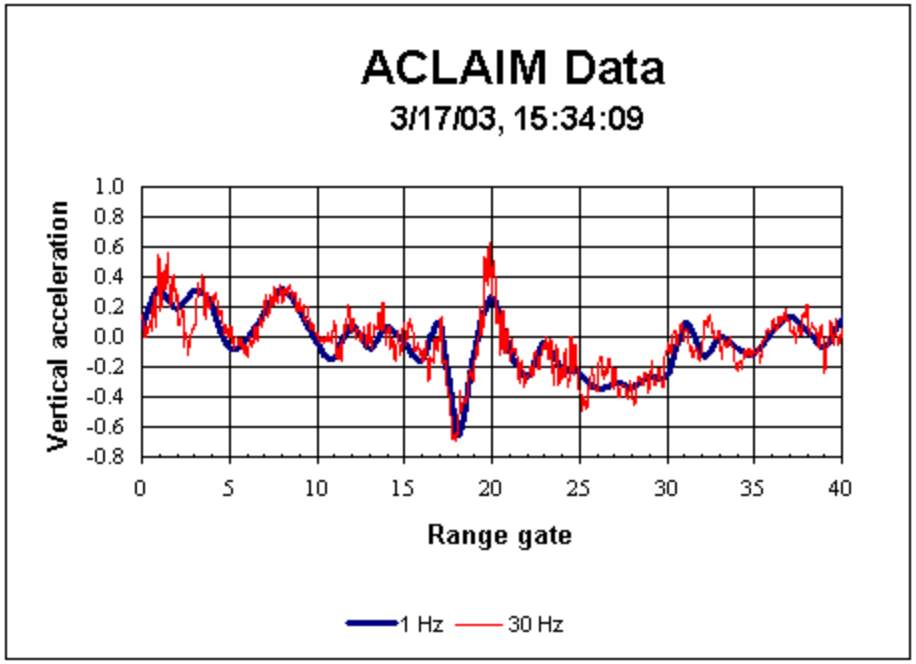

ACLAIM Data
3/17/03, 15:34:07
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

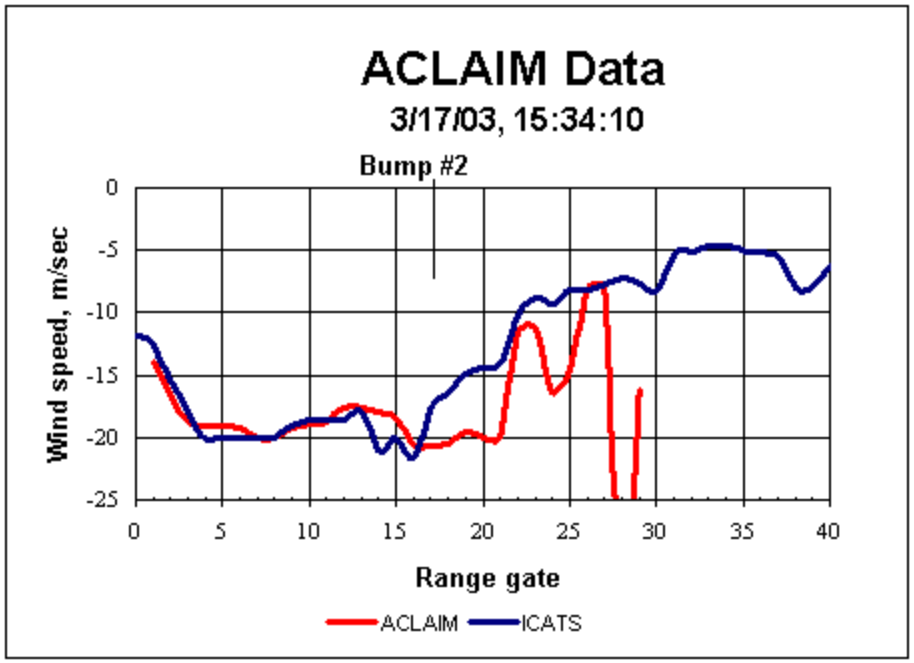

ACLAIM Data
3/17/03, 15:34:07
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

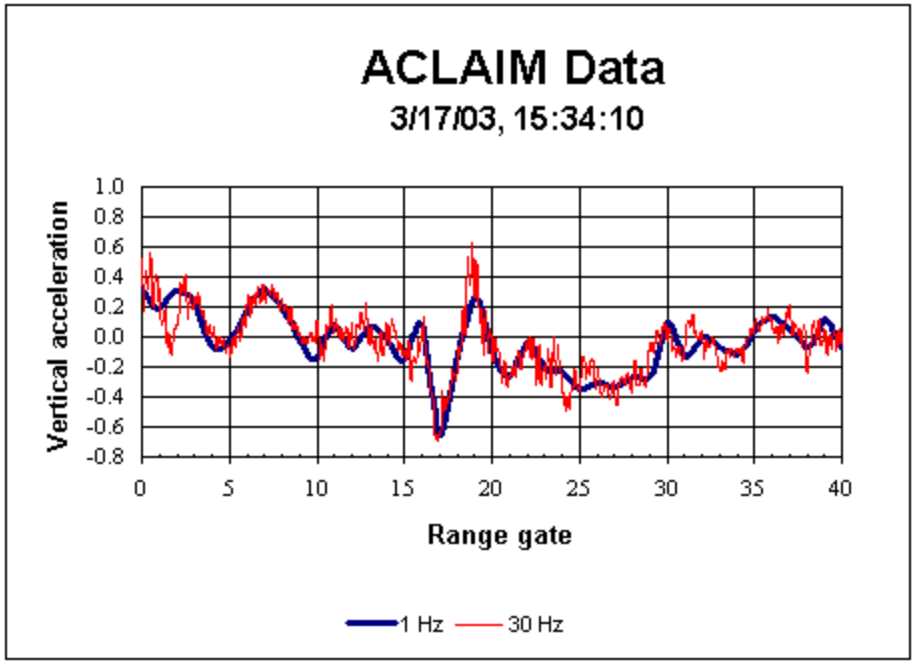

ACLAIM Data
3/17/03, 15:34:08
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

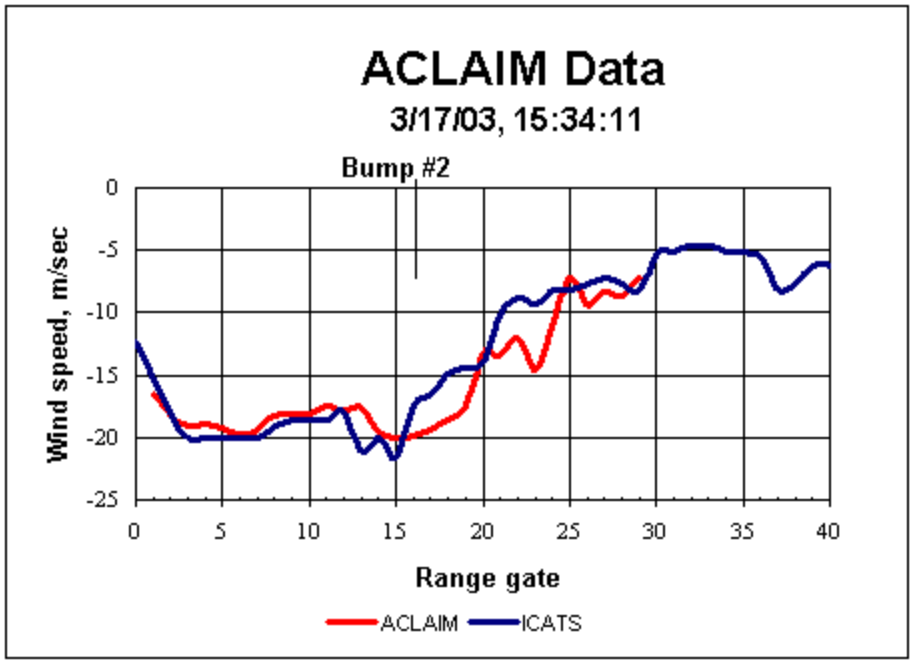

ACLAIM Data
3/17/03, 15:34:08
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

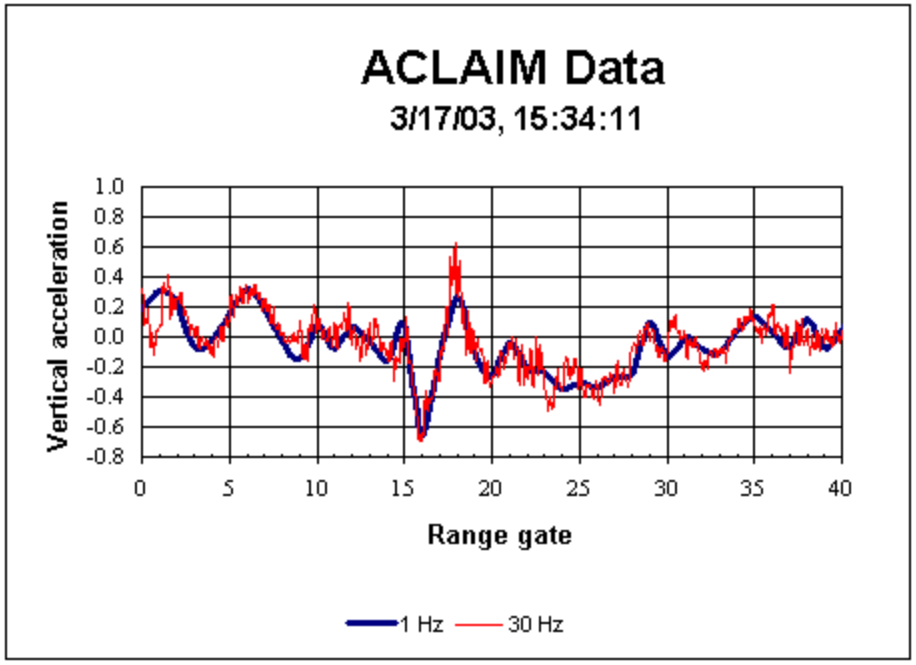

ACLAIM Data
3/17/03, 15:34:09
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

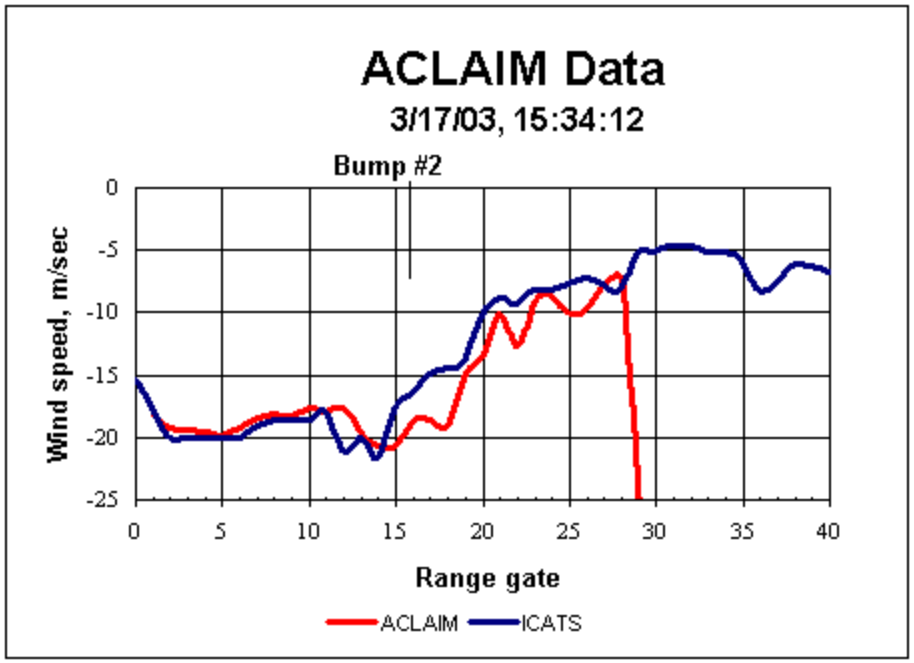

ACLAIM Data
3/17/03, 15:34:09
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

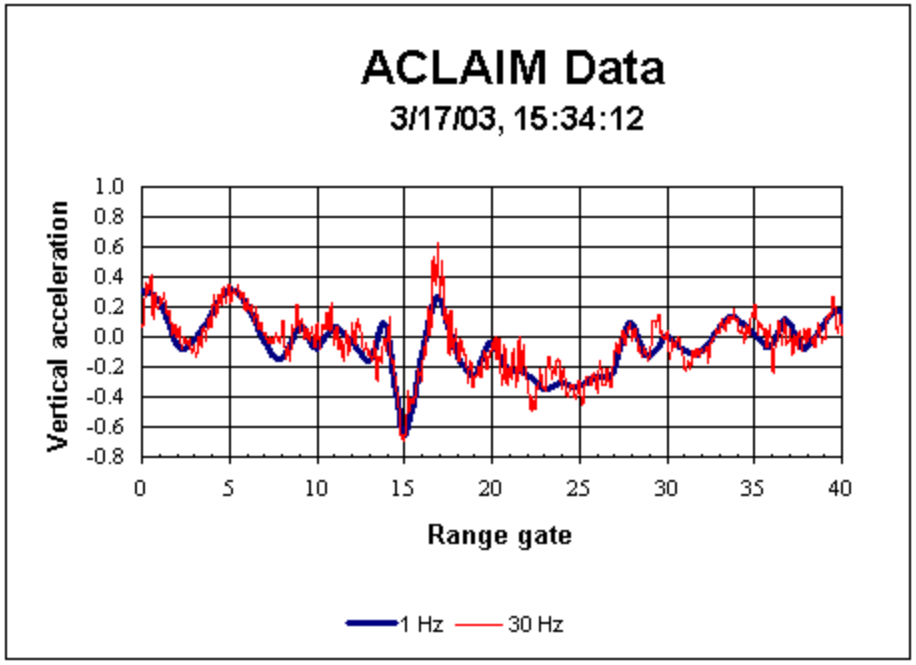

ACLAIM Data
3/17/03, 15:34:10
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

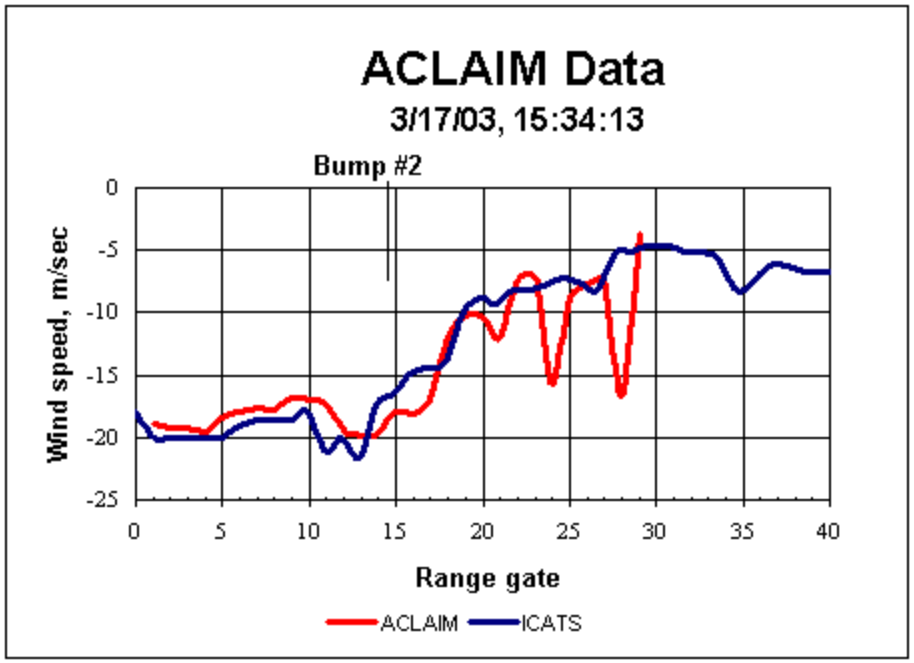

ACLAIM Data
3/17/03, 15:34:10
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

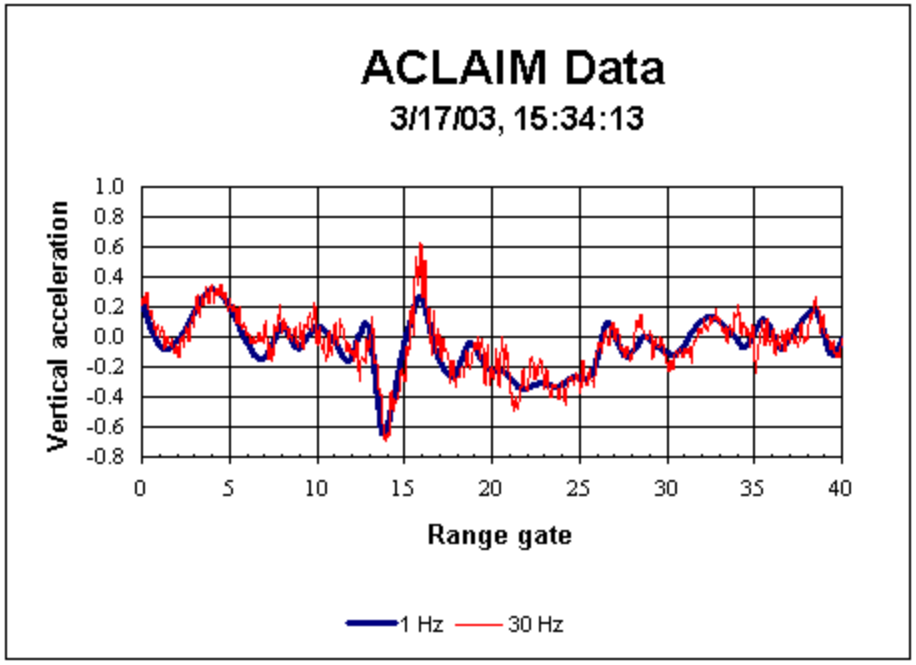

ACLAIM Data
3/17/03, 15:34:11
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

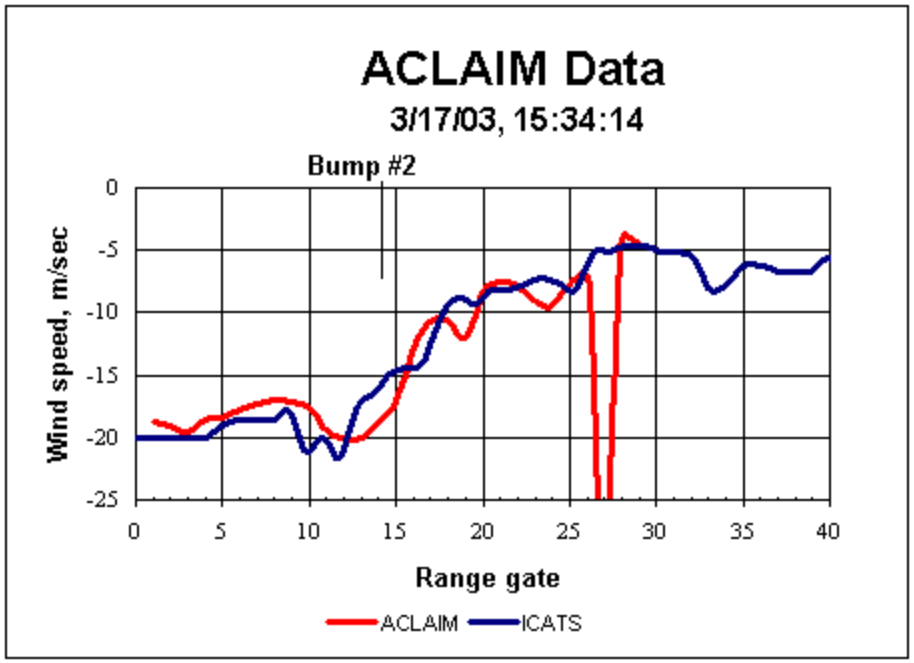

ACLAIM Data
3/17/03, 15:34:11
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

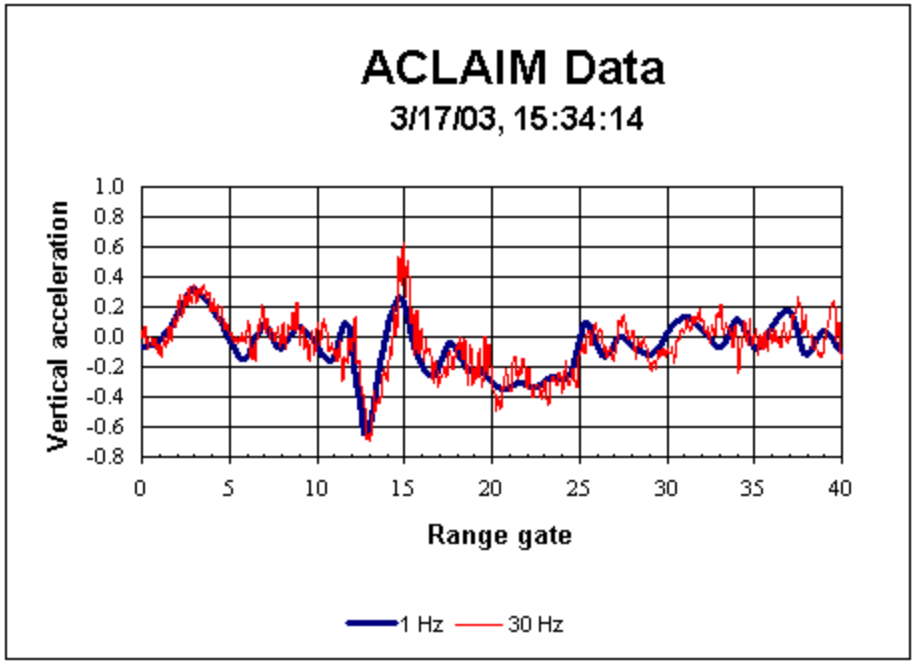

ACLAIM Data
3/17/03, 15:34:12
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

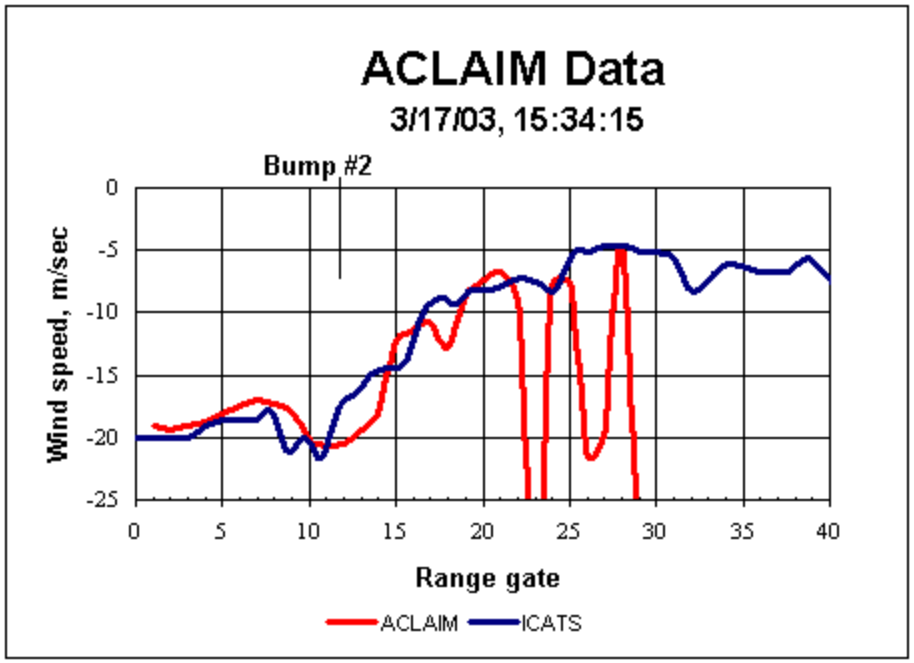

ACLAIM Data
3/17/03, 15:34:12
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

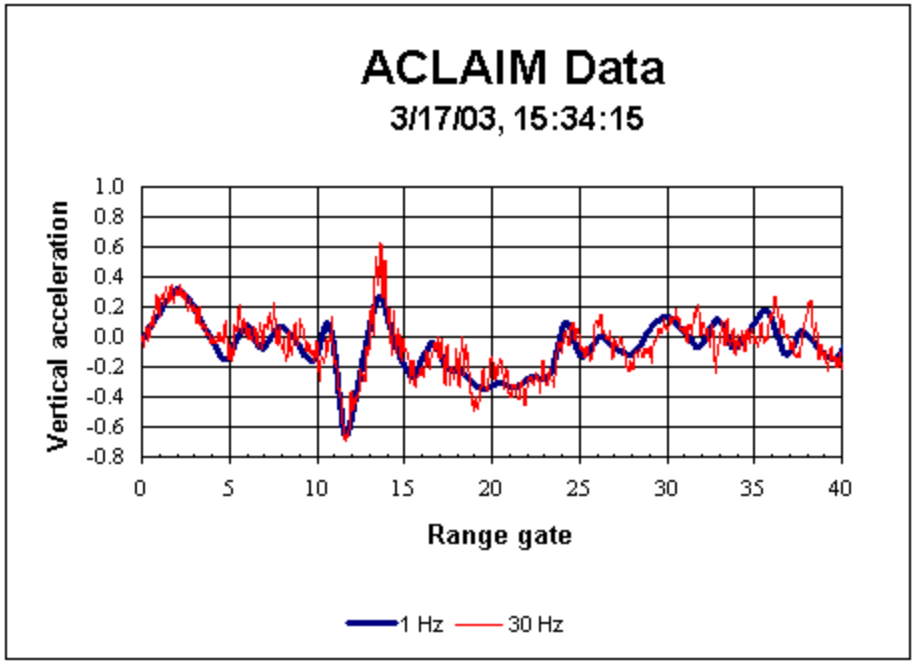

ACLAIM Data
3/17/03, 15:34:13
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

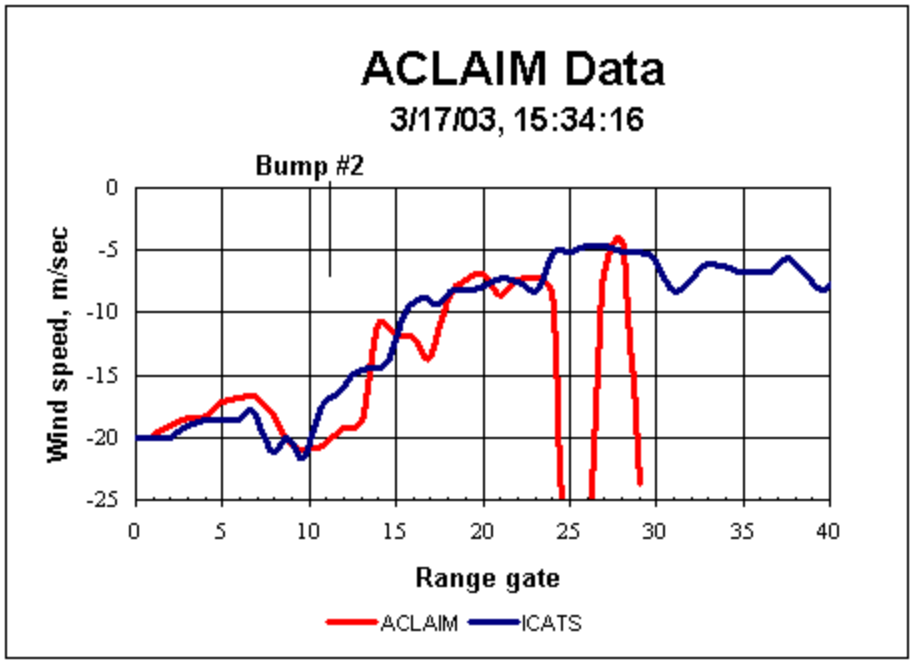

ACLAIM Data
3/17/03, 15:34:13
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

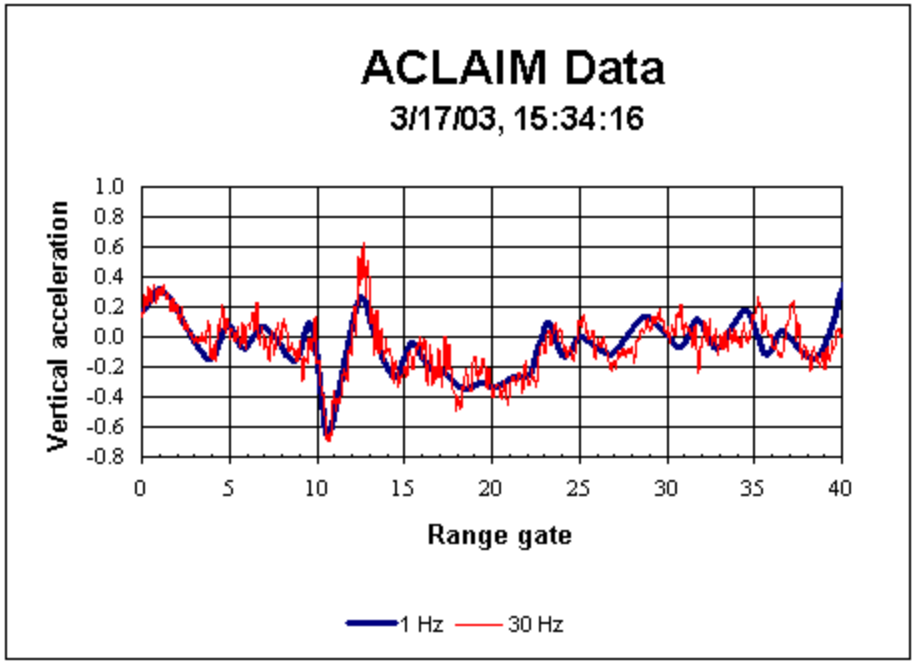

ACLAIM Data
3/17/03, 15:34:14
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

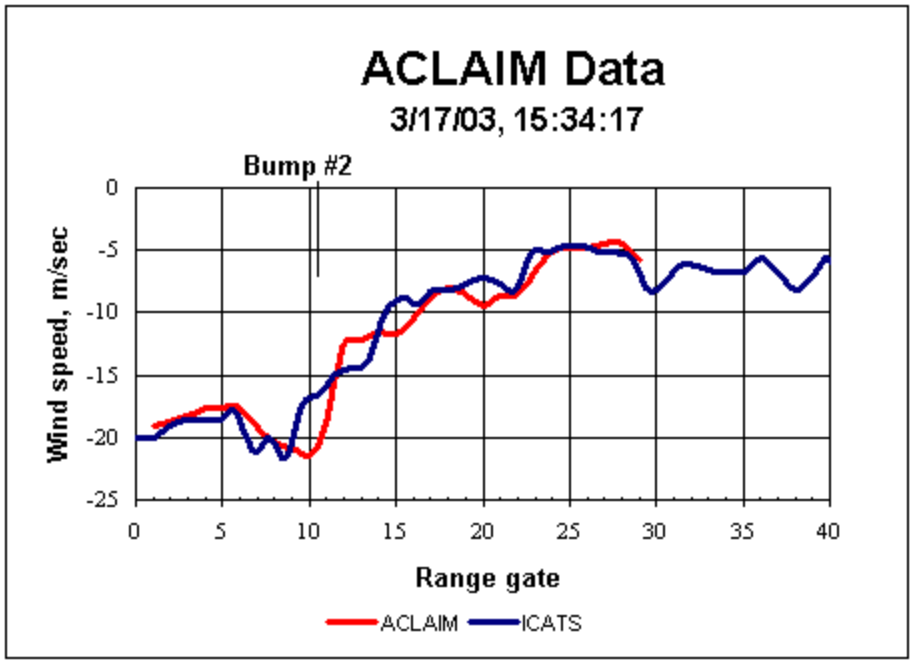

ACLAIM Data
3/17/03, 15:34:14
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

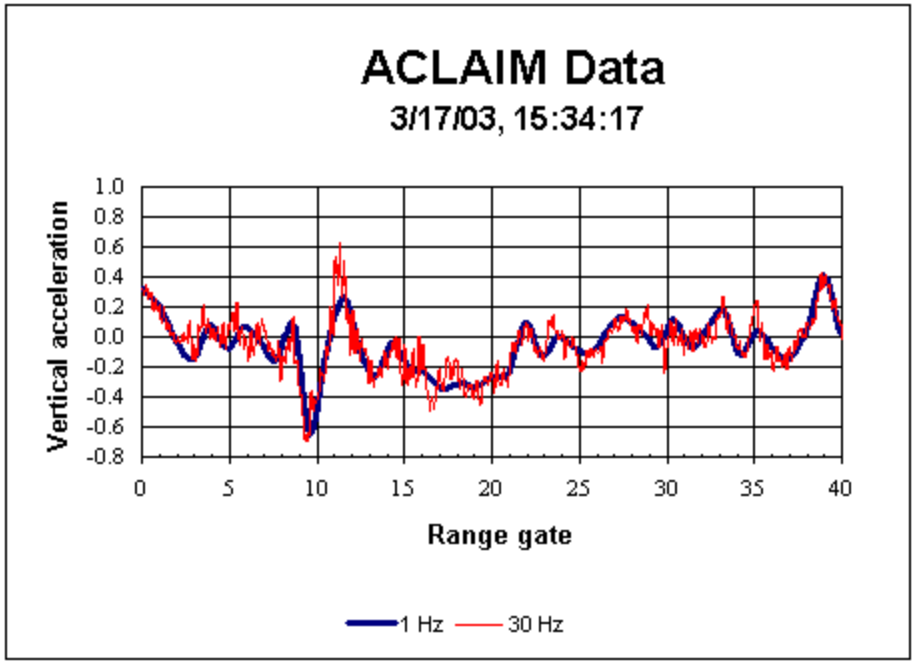

ACLAIM Data
3/17/03, 15:34:15
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

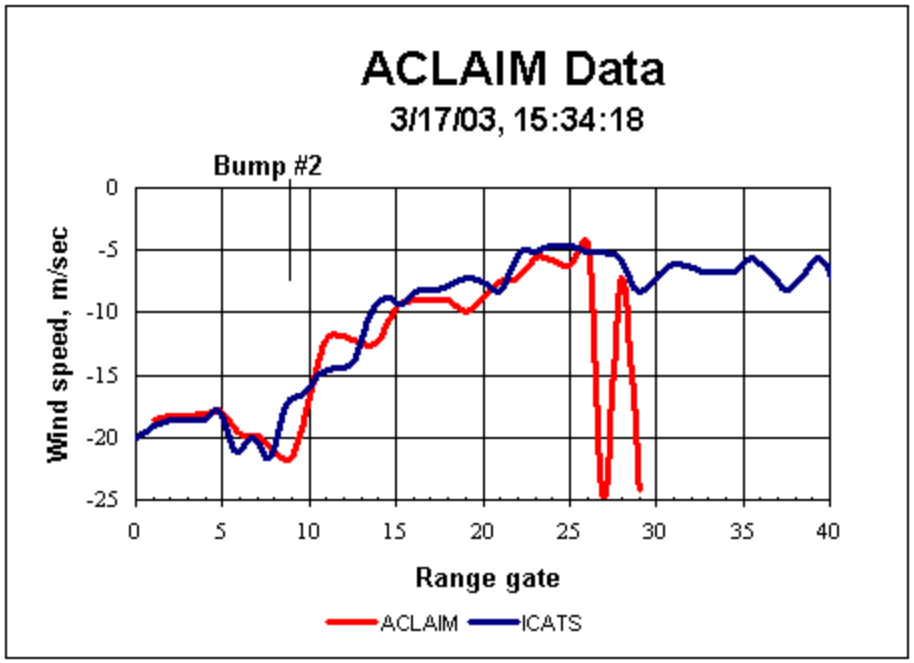

ACLAIM Data
3/17/03, 15:34:15
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

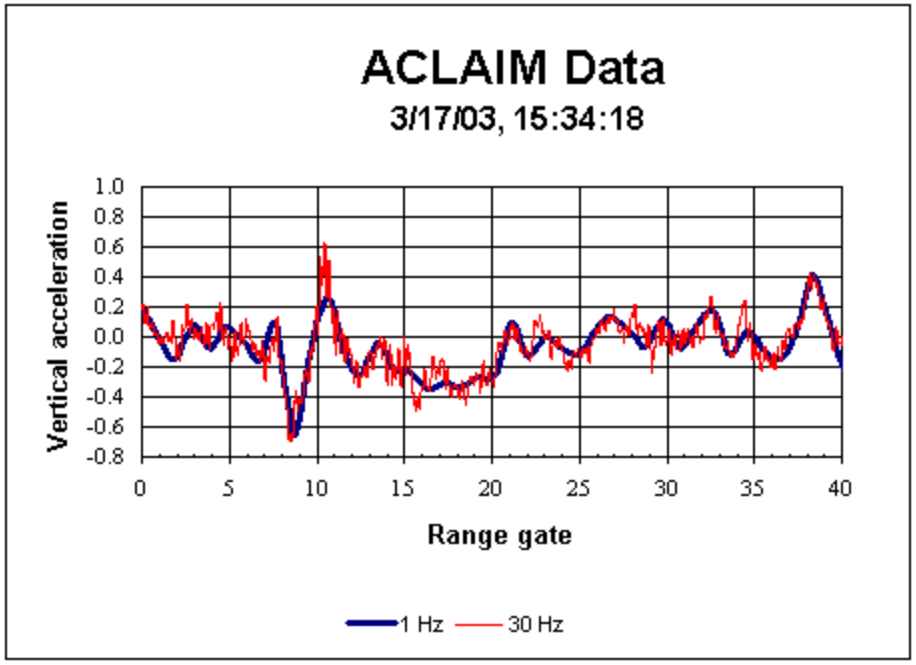

ACLAIM Data
3/17/03, 15:34:16
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

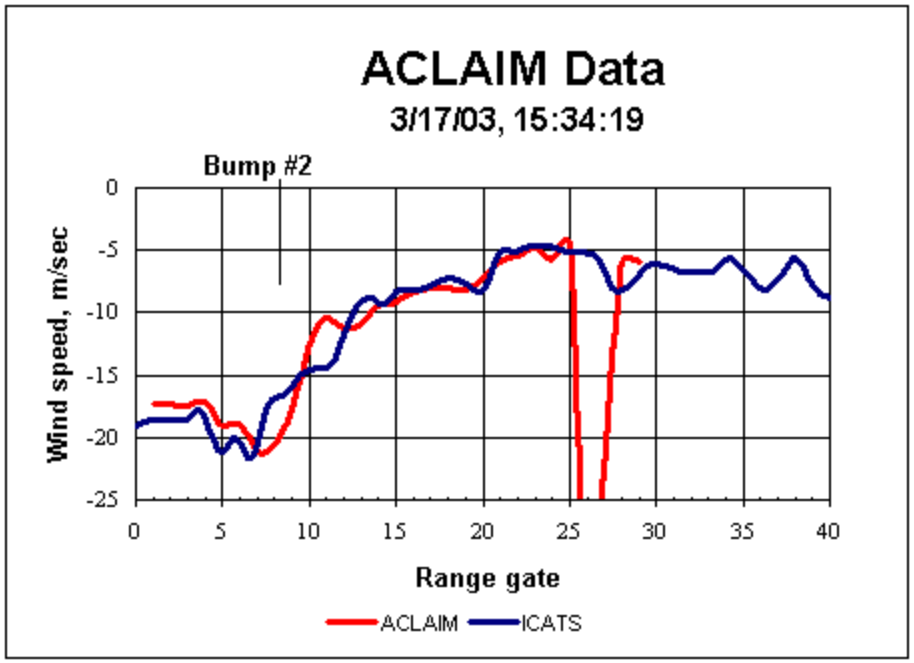

ACLAIM Data
3/17/03, 15:34:16
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

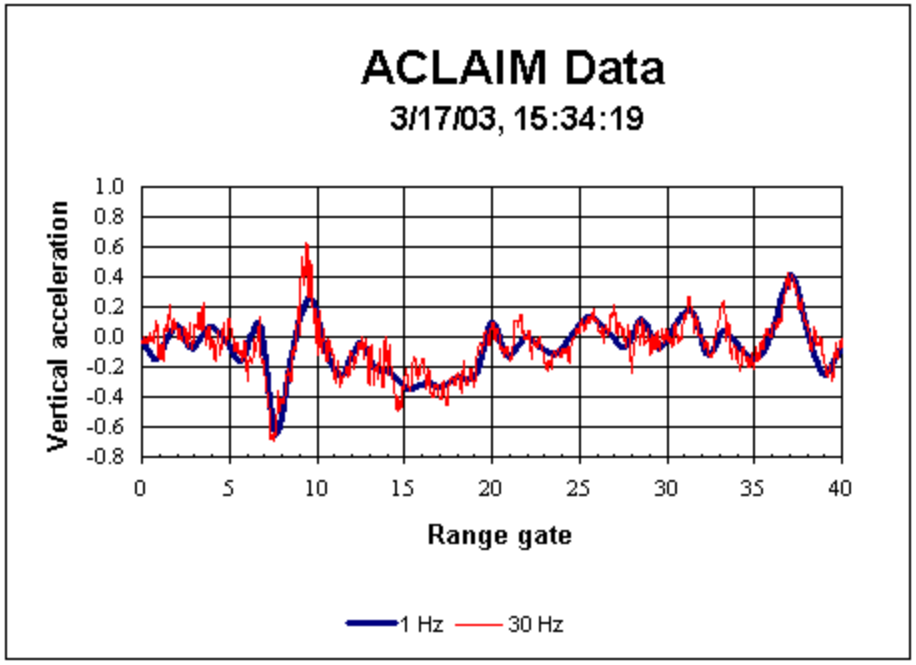

ACLAIM Data
3/17/03, 15:34:17
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

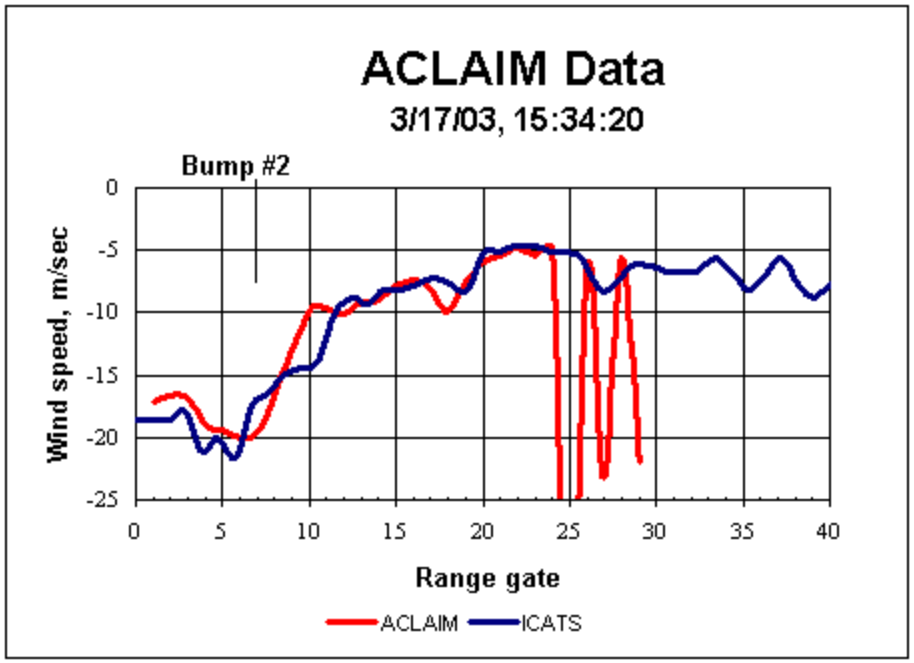

ACLAIM Data
3/17/03, 15:34:17
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

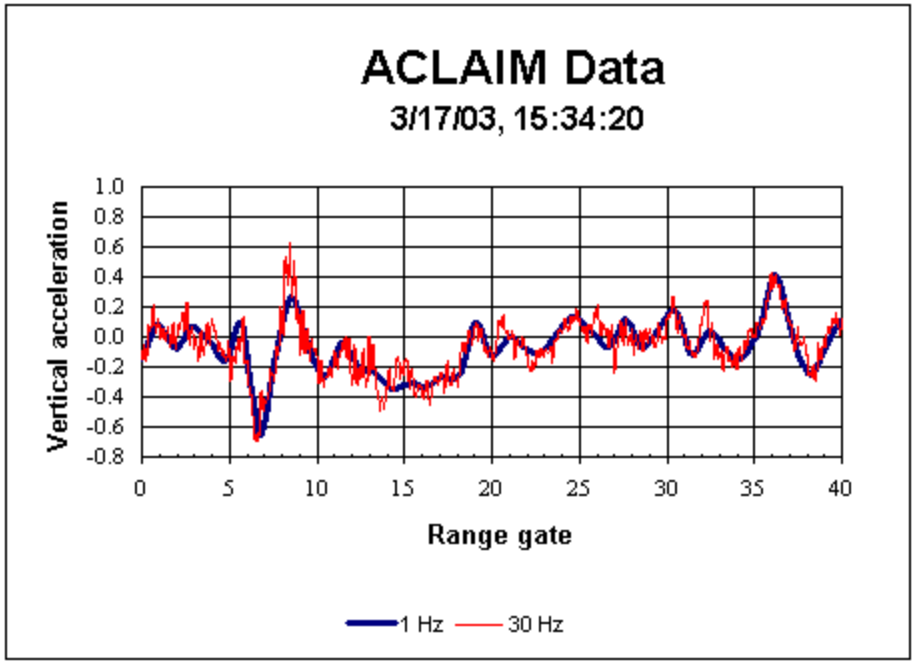

ACLAIM Data
3/17/03, 15:34:18
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

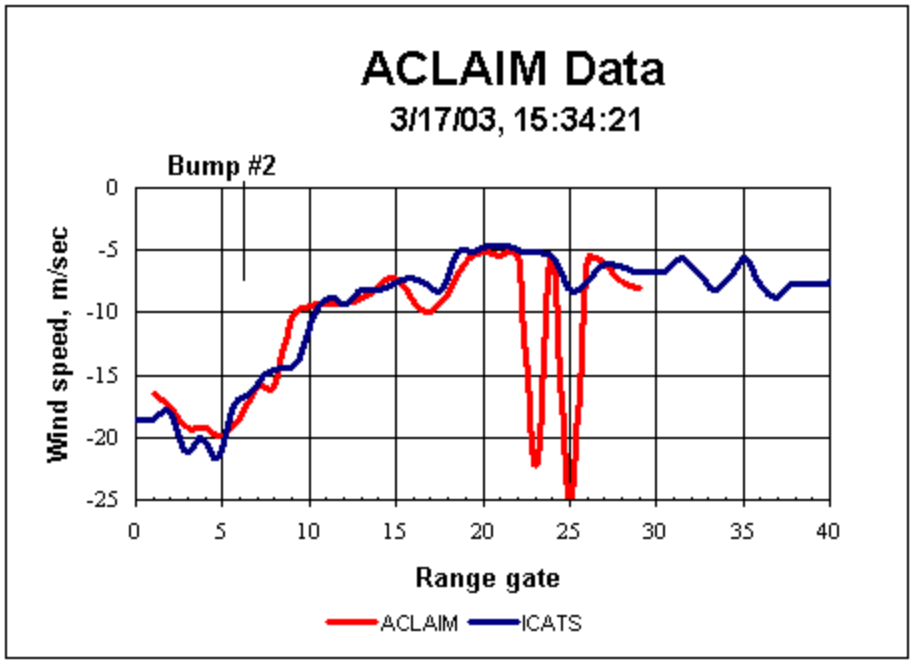

ACLAIM Data
3/17/03, 15:34:18
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

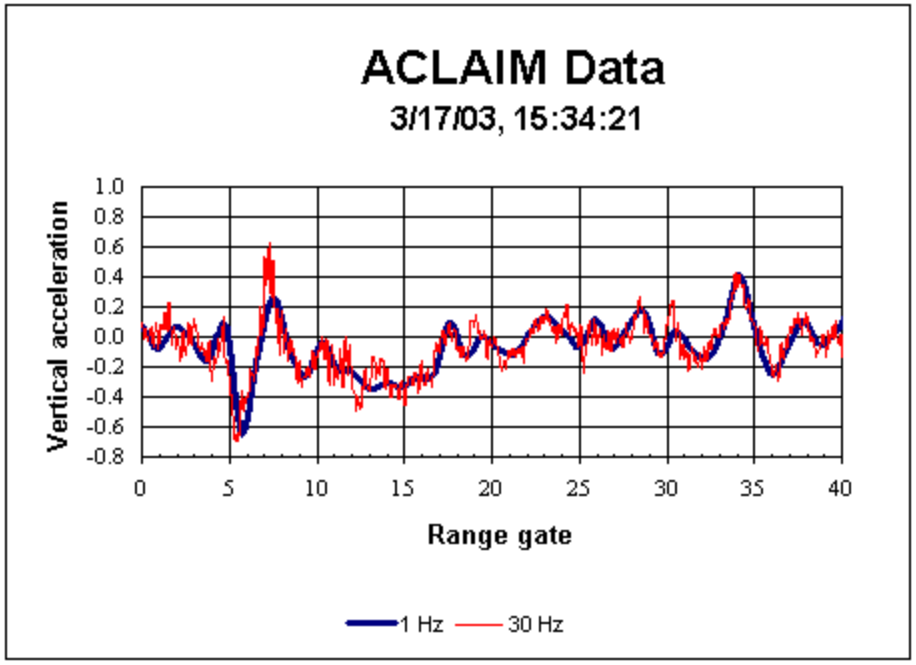

ACLAIM Data
3/17/03, 15:34:19
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

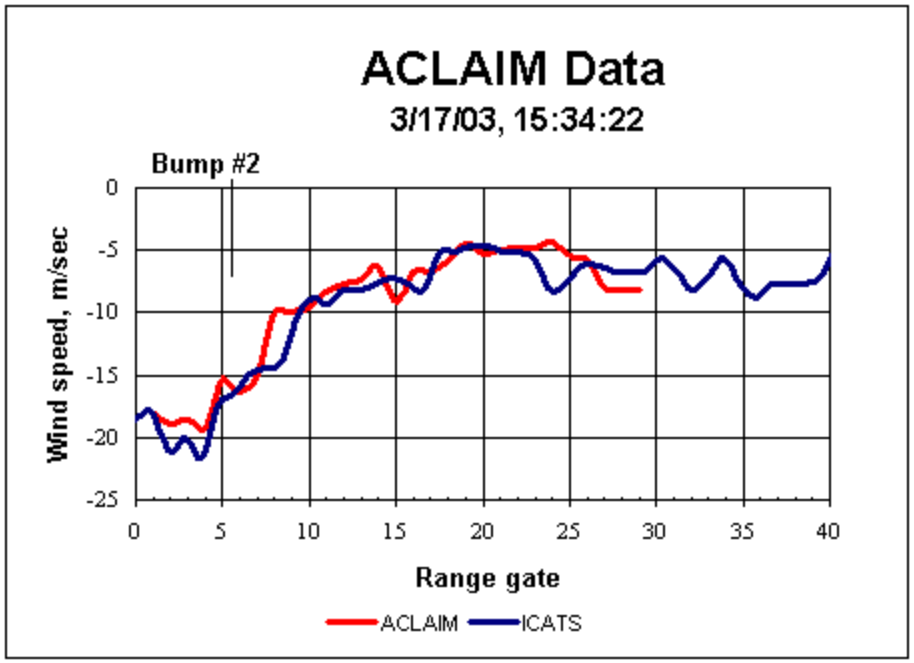

ACLAIM Data
3/17/03, 15:34:19
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

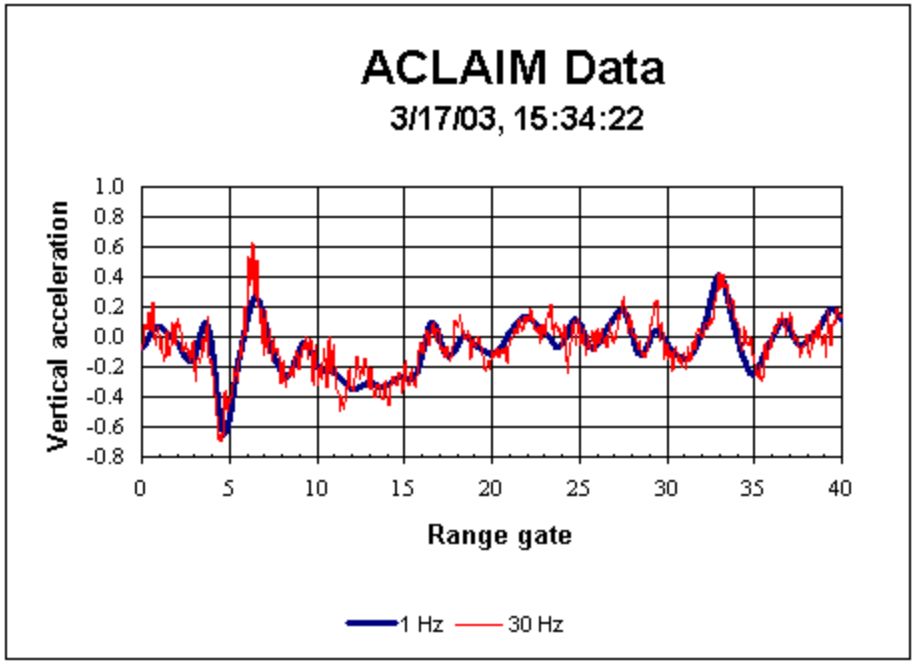

ACLAIM Data
3/17/03, 15:34:20
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

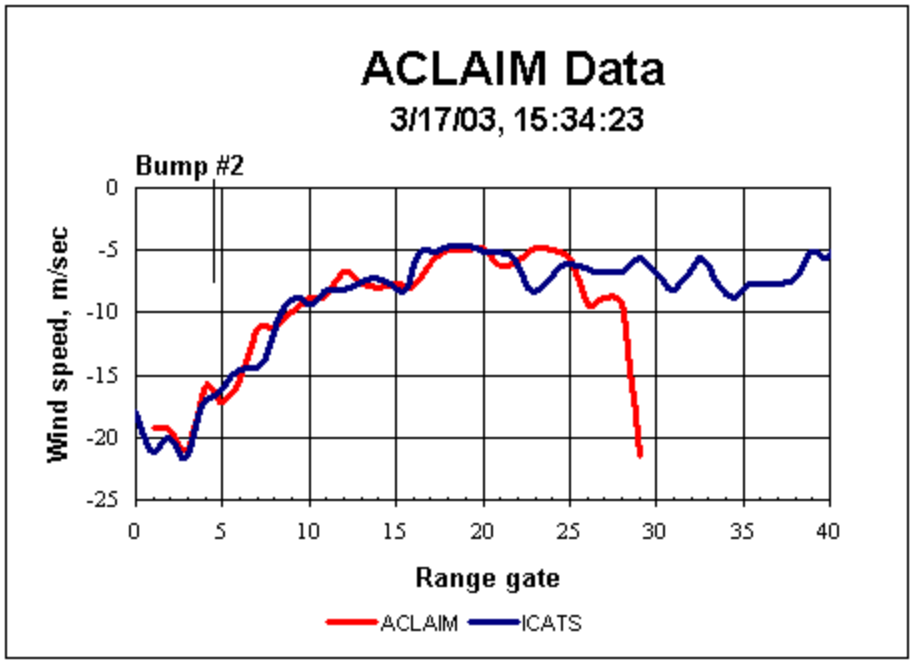

ACLAIM Data
3/17/03, 15:34:20
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

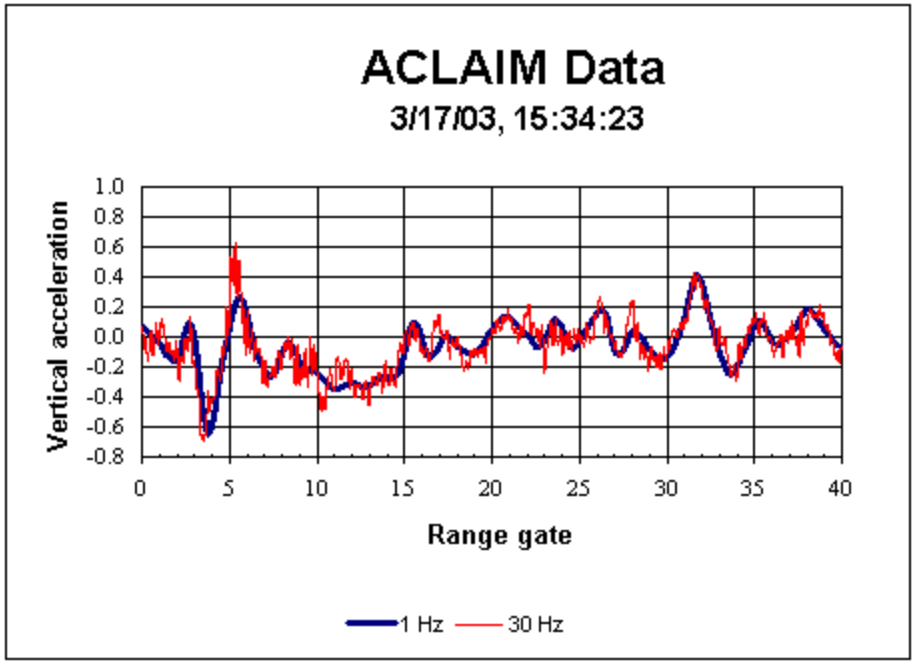

ACLAIM Data
3/17/03, 15:34:21
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

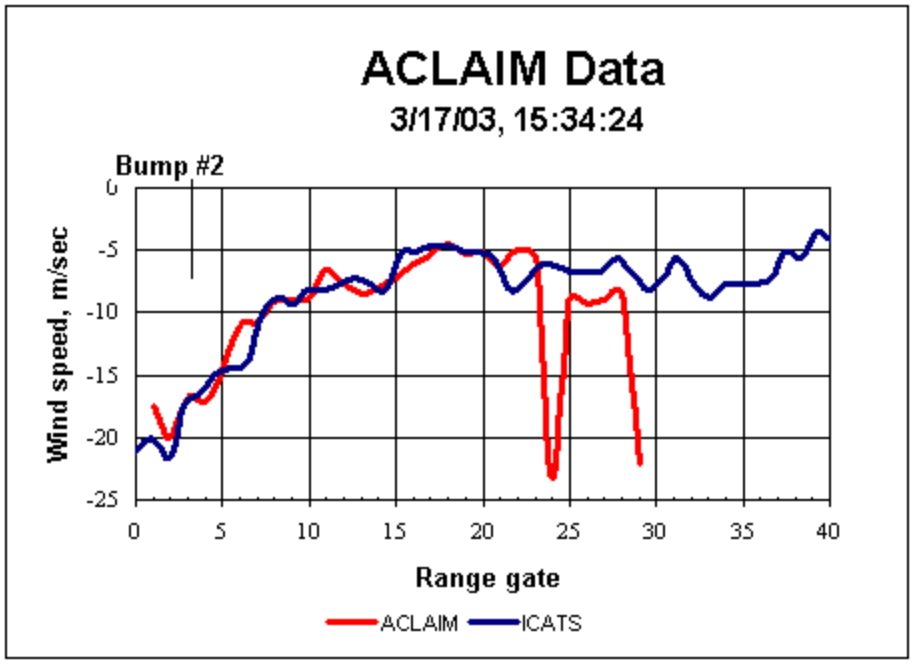

ACLAIM Data
3/17/03, 15:34:21
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

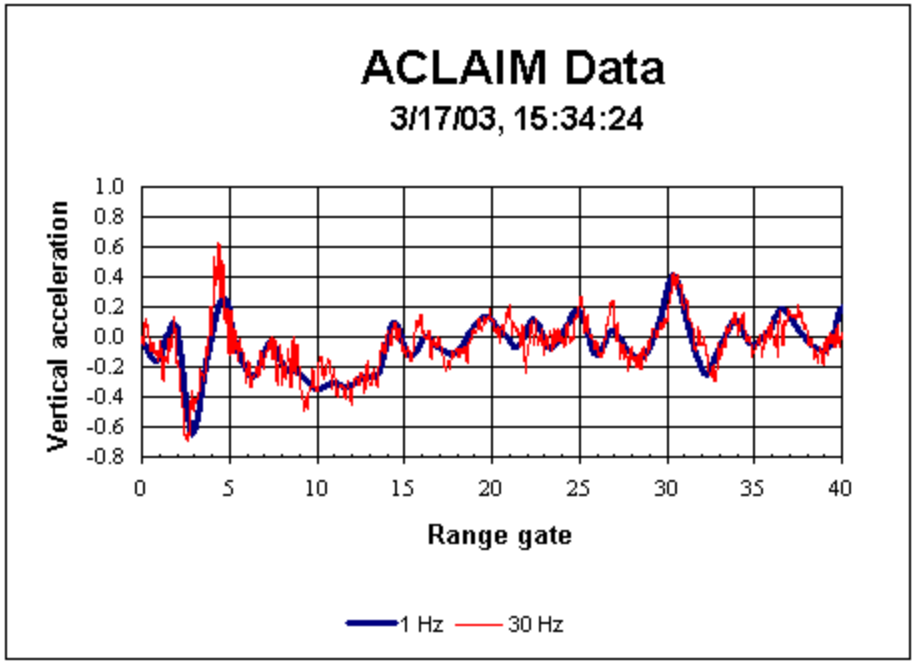

ACLAIM Data
3/17/03, 15:34:22
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

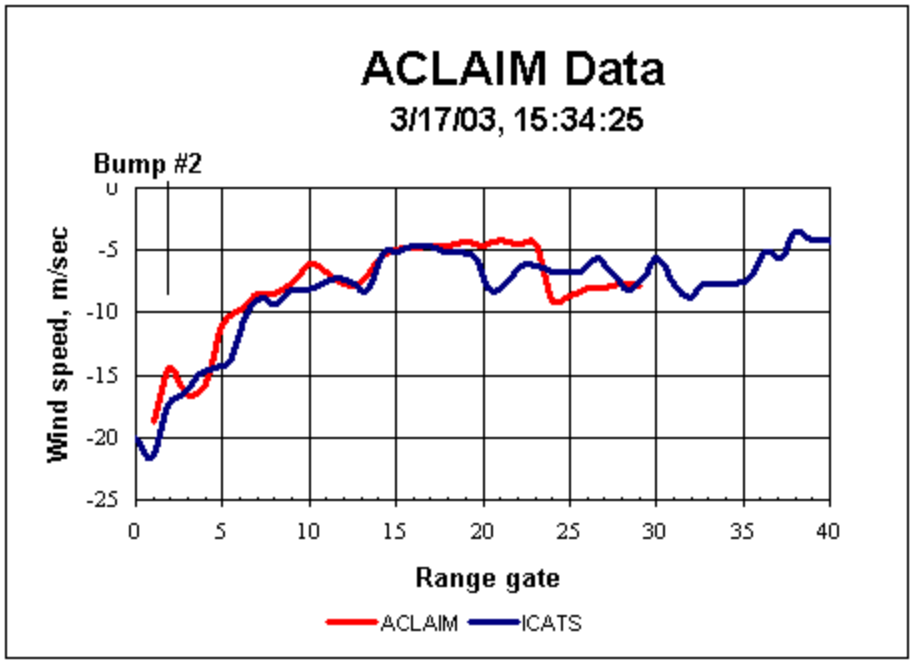

ACLAIM Data
3/17/03, 15:34:22
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

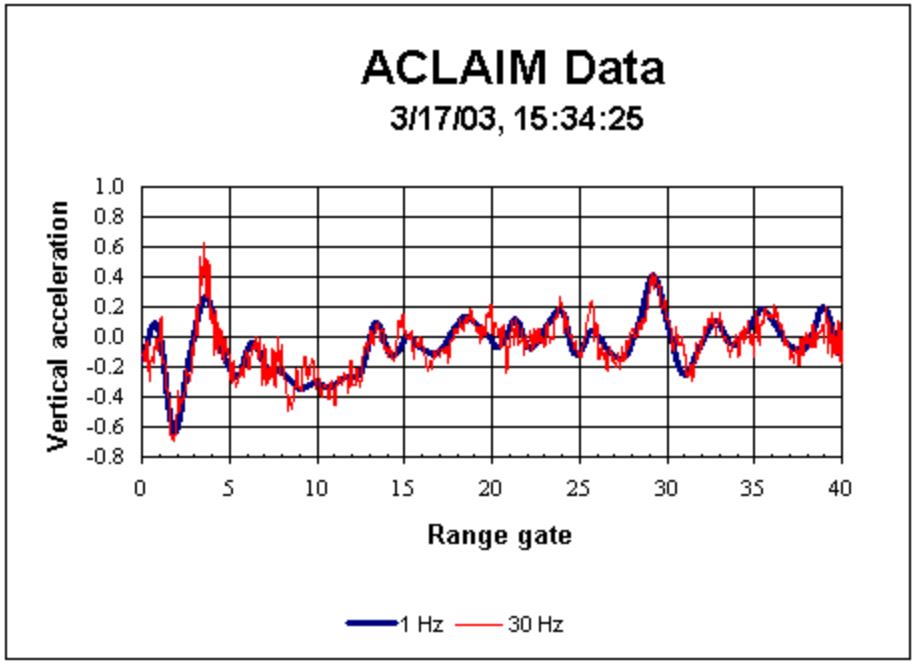

ACLAIM Data
3/17/03, 15:34:23
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

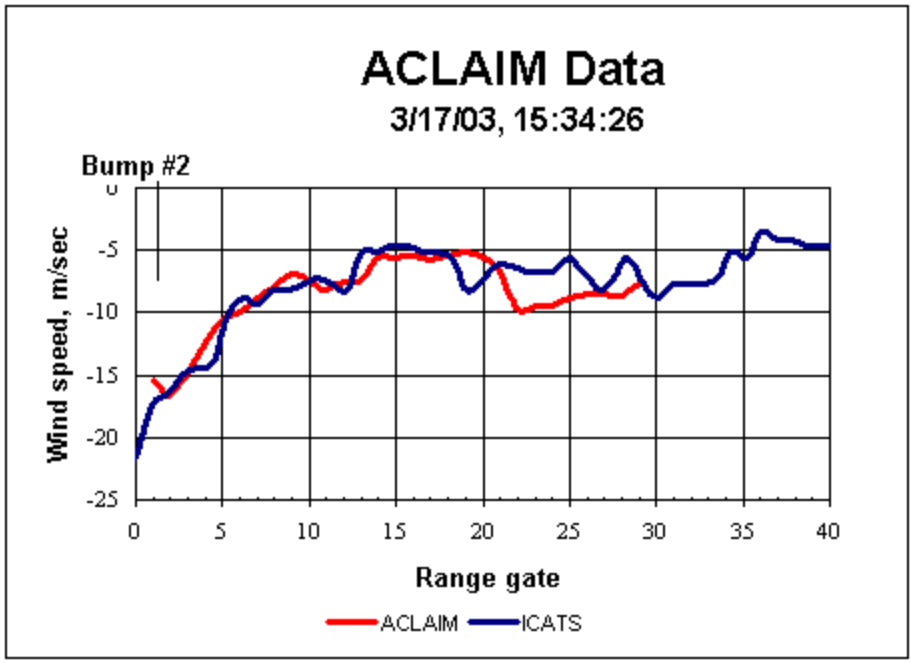

ACLAIM Data
3/17/03, 15:34:23
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

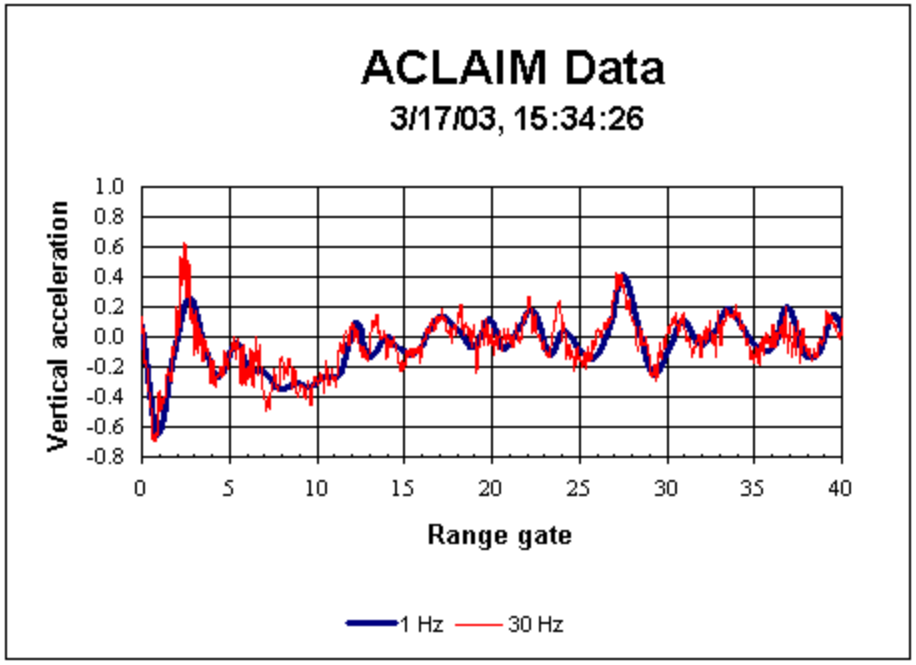

ACLAIM Data
3/17/03, 15:34:24
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

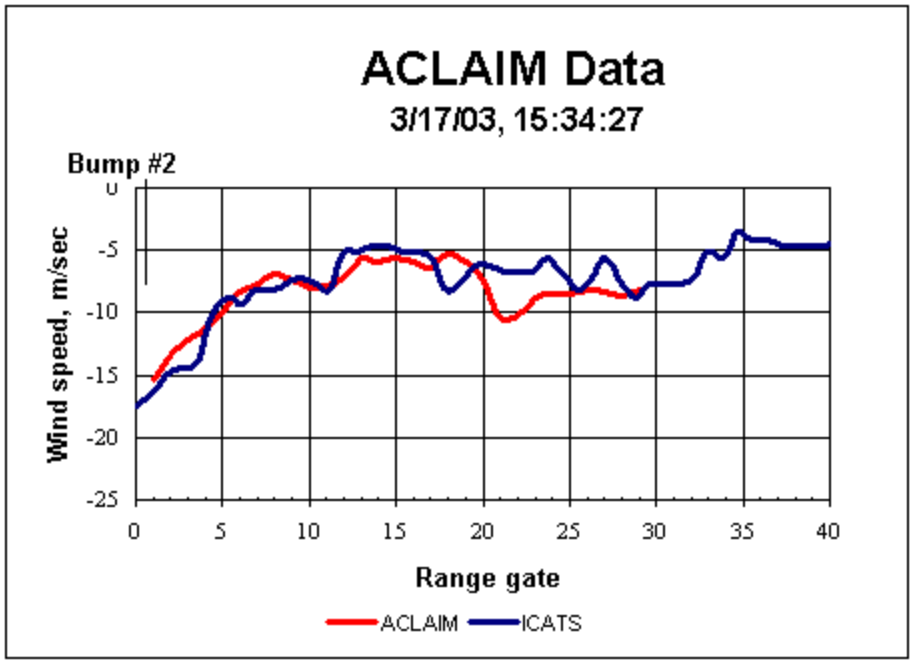

ACLAIM Data
3/17/03, 15:34:24
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

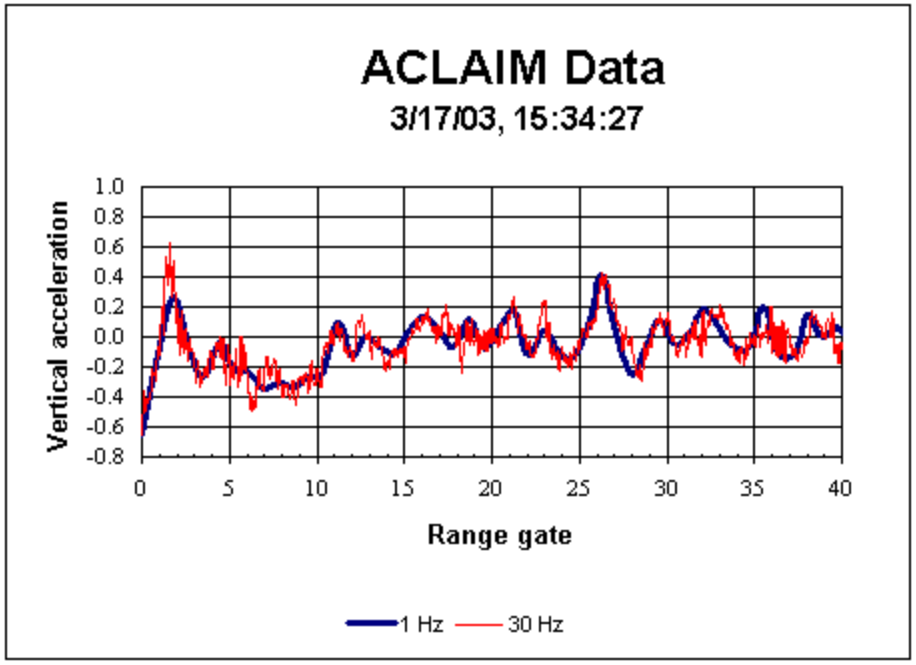

ACLAIM Data
3/17/03, 15:34:25
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS

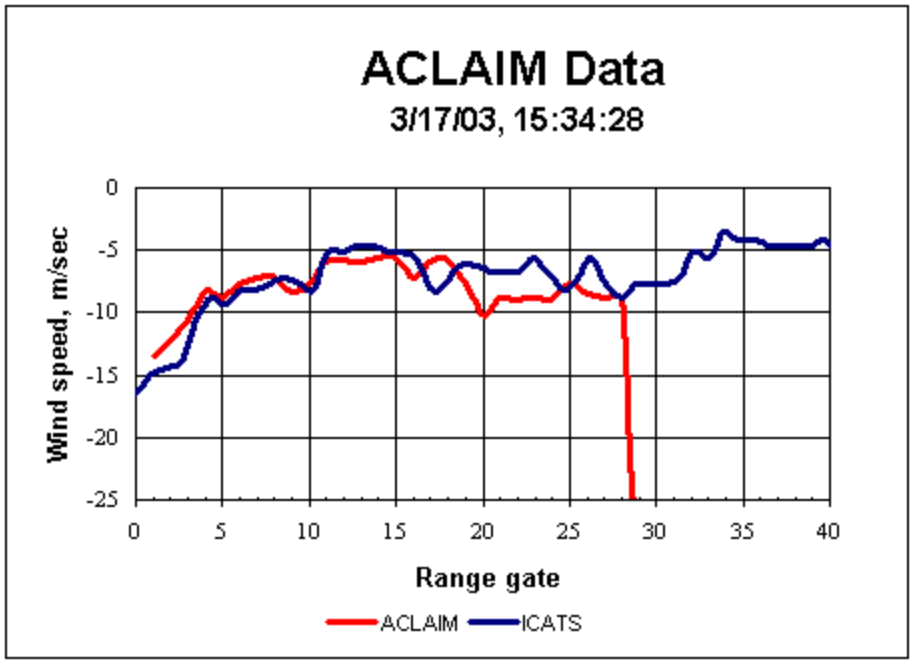

ACLAIM Data
3/17/03, 15:34:25
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

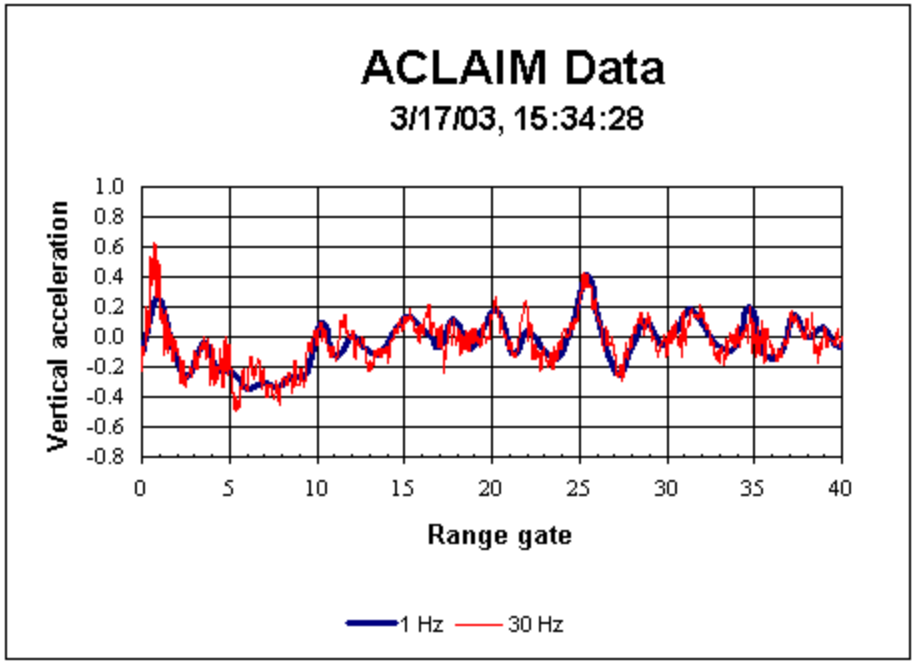

ACLAIM Data
3/17/03, 15:34:26
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS


ACLAIM Data
3/17/03, 15:34:26
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz


ACLAIM Data
3/17/03, 15:34:27
Bump #2
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS


ACLAIM Data
3/17/03, 15:34:27
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz


ACLAIM Data
3/17/03, 15:34:28
Wind speed, m/sec
0
-5
-10
-15
-20
-25
0
5
10
15
20
25
30
35
40
Range gate
ACLAIM
ICATS


ACLAIM Data
3/17/03, 15:34:28
Vertical acceleration
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35
40
Range gate
1 Hz
30 Hz

Summary

- **Demonstrated CAT detection**
  - TAS and Lidar highly Correlated
- **Validated backscatter model and scaling laws**
  - Needed for next generation design
- **Achieved range in clear air @ 30-40 kft MSL**
  - 2 km demonstrated > 90 % of the time
  - 6-12 km in sub-visible Cirrus

Follow-on Efforts

- Begin the move to 1.55 micron system with higher power
- Evaluate scanning strategies and algorithms for detailed turbulence characterization
- Verify all-weather coverage for turbulence prediction and warning for combined Radar/Lidar systems